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PROCESSING AND APPLICATIONS OF
DEPLETED URANIUM ALLOY PRODUCTS

BATTELLE COLUMBUS LABORATORIES
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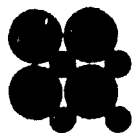
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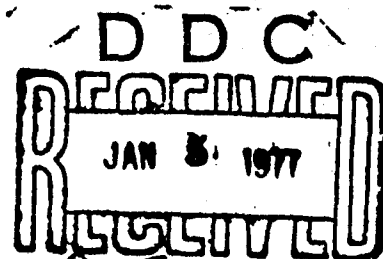
PROCESSING AND APPLICATIONS OF DEPLETED URANIUM ALLOY PRODUCTS

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Depleted uranium alloys can be shaped into parts by conventional metal processing. The main problem is reactivity with the atmosphere. Uranium is about as pyrophoric as magnesium.

Possible applications for depleted uranium include counterweights, radiation shielding, ammunition, weapons, and ballast.

MCIC Report/September 1976

PROCESSING AND APPLICATIONS OF DEPLETED URANIUM ALLOY PRODUCTS

Carl T. Olofson, George E. Meyer, and Albert L. Hoffmann
Battelle's Columbus Laboratories

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FINAL REPORT
on
PROCESSING AND APPLICATIONS OF
DEPLETED URANIUM ALLOY PRODUCTS

to
METALS AND CERAMICS
INFORMATION CENTER
(MCIC)

by
Carl T. Olofson, George E. Meyer, and Albert L. Hoffmanner

August 6, 1976

SUMMARY

Depleted uranium is produced from the tailings (UF_6) of the uranium enrichment process for nuclear power. The depleted uranium fraction contains approximately 99.8 percent U^{238} and 0.2 percent U^{235} . Its radioactivity level is low, approximating the hazards of a radium-dial watch. Efforts are underway to utilize this material in nonnuclear applications since its supply is large and growing.

Uranium, one of the most dense metals, has a density of 18.7 g/cc. It work hardens readily and exhibits pronounced anisotropy. A wide variation in mechanical properties can exist depending on metal purity. Mechanical properties of uranium can also be changed by alloying. Uranium alloys can exhibit much higher room-temperature strengths, improved corrosion resistance, and higher creep strengths than the pure metal.

The main hazards of fabricating depleted uranium include heavy metal toxicity of airborne particulates (similar to lead) and its potential pyrophoricity (similar to magnesium). All operations must be vented through exhaust lines to collection points. The residues, as well as chips from machining operations, are then disposed in a prescribed manner specified by the U.S.A. NRC (Nuclear Regulatory Commission). The toxicity of such products is largely related to the high density of uranium, and the resulting dangers of heavy metal poisoning.

Depleted uranium and its alloys can be shaped into parts by conventional metal processing. The main problem is chemical reactivity with ambient atmosphere. Precision casting methods employed include investment casting and permanent mold casting. Uranium ingot also can be rolled, forged, extruded, and drawn successfully as long as it is not in the beta allotropic state. Uranium can be machined by standard shop practices provided certain precautions are taken to minimize work hardening and high cutting temperatures. Some intermetallics in uranium can be very abrasive to cutting edges, and reduce tool life accordingly.

Depleted uranium and its alloys have found applications as counterweights, radiation shielding, ammunition, weapons, gyroscopes, and ballast. Depleted uranium used in fly-wheel devices, nuclear fuel casks, and ammunition could consume a significant amount of metal. The electrical properties of uranium oxides and uranates appear to be useful in the construction of fuel cells, incandescent lamps, thermistors, and as ultraviolet light-sensitive elements in photoelectric tubes.

The size and nature of the future depleted uranium market are uncertain. Since the current non-nuclear applications are economically sound, they should continue to consume small quantities of this uranium. The high density of the metal and its capability to form useful alloys could foster the development of new and specialized applications which would increase its consumption considerably.

INTRODUCTION

Depleted uranium (DU) is produced from the UF_6 tailings of the uranium enrichment process to provide U^{235} uranium for nuclear-power reactors. Both products result from an isotope separation of natural uranium which normally contains 99.3 percent of U^{238} , 0.7 percent of U^{235} , and 0.005 percent U^{234} . The depleted uranium fraction has a composition of approximately 99.3 percent U^{238} and 0.2 percent U^{235} . Although the fission-chain reaction could operate with natural uranium, uranium enriched in the U^{235} isotope is normally used in nuclear-power operations⁽¹⁾.

Three large plants with a total investment of over three billion dollars generate the enriched and depleted uranium products in the United States. It is estimated that an inventory of about 165,000 metric tons of depleted uranium as UF_4 and UF_6 became available as of January 1, 1970 as a result of prior separations. Furthermore, estimated needs for enriched uranium indicate that an additional 230,000 metric tons of DU will be produced before midyear 1980. Therefore, an expansion of known uses, and the development of new uses in tonnage quantities is of considerable interest for this material in nonnuclear applications⁽¹⁾.

The purpose of this report is to present property, processing and fabricating information for depleted uranium alloys which could lead toward a more extensive use of this material. The basic source of metal supply would be the existing inventory of depleted uranium fluorides which is large and growing.

BACKGROUND INFORMATION

ORE-TO-METAL PROCESSING

Uranium ores are chemically processed by a sequence of digestion, extraction, separation, and purification techniques to produce uranium trioxide.* Subsequent treatments reduce the trioxide to uranium dioxide which is then hydrofluorinated to a green salt containing 97.5 percent uranium tetrafluoride (UF_4) and 1.5 percent uranium oxyfluoride, the remainder being unconverted uranium oxides (UO_3 and UO_2). The processing road divides beyond the green salt stage, one route leading to fertile natural uranium, the other route to enriched uranium and its by-product depleted uranium.⁽²⁾

The natural uranium route is comparatively short and straightforward. It involves only a few chemical processing operations, including a chemical reduction at high temperature using magnesium as the reducing agent. Most of the natural uranium so produced becomes the starting material for making plutonium.

The enriched uranium/depleted uranium route is longer, more complicated, and very costly. The green salt (UF_4) is first fluorinated into a corrosive uranium hexafluoride gas (UF_6) which is then pumped through a series of isotope diffusion-separation stages operating under partial vacuum. The separation process is instrumented heavily to closely control the efficiency of separating UF_6 into two hexafluoride fractions, enriched and depleted. The enriched fraction of hexafluoride gas flowing out of the last stage is collected as a solid by cold trapping and then subsequently reduced, as required, by magnesium fines to solid enriched uranium and MgF_2 slag. The enriched uranium metal product from this reduction has the form of a rimless derby, from which the generic term "derby" originated.

The depleted fraction is also accumulated as a solid and stored either as UF_6 or the reduced product UF_4 . Both are very high purity. Although the current demands for depleted uranium are small and greatly exceeded by its production, both the requirement for hydrogen fluoride (HF), and the inventory of UF_6 storage vessels are sufficiently great at ERDA facilities to make the reduction of UF_6 to UF_4 and HF cost effective. Therefore, both depleted UF_6 and UF_4 (in 55-gallon drums), are stored, and the HF (obtained from the reduction of UF_6) is used for the fluoridation of beneficiated ore (UO_3) to UF_6 for subsequent enrichment. The exact value of the U^{235} content in DU stored as depleted UF_6 and UF_4 is classified but is less than 0.3 percent. With the current anticipated increases in nuclear-energy requirements, further processing of depleted UF_6 (now stored) is anticipated. However, this reprocessing is currently limited by the diffusion-separation capacity of the U.S. facilities.

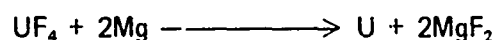
Depleted-uranium green salt quality typical of the as-reduced and screened (-8 mesh) UF_4 product reduced from the UF_6 tailings from the diffusion-separation process are shown in Table 1.⁽³⁾ The major impurity elements are copper, iron, and nickel primarily from container rust during handling, and such inadvertently included components such as scale from the reduction system. Uranium oxides, uranyl fluoride, residual UF_6 , HF and H_2O from the UF_6 , or products of reaction of the included UF_6 and UF_4 with moisture during improper storage of the UF_4 also could be present.

* Also called orange oxide.

TABLE 1. CHEMICAL AND PHYSICAL PROPERTIES OF SEPARATION
PLANT-REDUCED GREEN SALT (UF_4)⁽³⁾

Trace Elements (ppm)	Cu	Al	Fe	Ni	Si	Mg
• Average	7	<4	6	12	<5	4
• Standard deviation	8		4	10		
U^{235} , percent	<0.3					
UO_2F_2 , percent						
• Average	0.11					
• Standard deviation	0.18					
Ammonium Oxalate Insolubles (AOI) percent						
• Average	0.26					
• Standard deviation	0.20					
Moisture (H_2O) Content, percent						
• Average	0.02					
• Standard deviation	0.02					
Bulk Density (lb/in.^3)	140 to 210					
Sieve Analysis, percent						
-20 mesh	94 to 99					
+80 mesh	1 to 8					

To produce depleted uranium metal, the UF_4 , which contains 75.6 percent uranium, is blended with a nearly stoichiometric quantity of magnesium granules (calcium has also been used)⁽²⁾, and heated in a graphite or MgF_2 -slag-lined steel vessel ("bombo") until the exothermic reaction -



is ignited. This reaction is usually selfsustaining after preheating to 1000 to 1500 F. The molten uranium droplets filter through this reacting blend and collect as a derby in the bottom of the reduction vessel with a yield (on a uranium basis) of about 92 percent. Reduction vessels in use in the U.S.A. and Canada provide 400 to 4500-pound derbies. The DU derby produced from diffusion-plant UF_4 exhibits the typical chemistry shown in Table 2. The major impurity elements in this product are associated with the purity of the UF_4 and magnesium, and primarily are iron, silicon, and magnesium from the magnesium.⁽³⁾ In subsequent vacuum melting, the magnesium is volatilized and removed, but the other elements usually remain. For conversion to metal products, the derby is remelted, usually with scrap uranium, adjusted with alloying additives, if required, and then cast into various shapes, usually ingot under vacuum of at least 1000 microns, or back-filled argon atmosphere.

TABLE 2. TYPICAL DERBY CHEMISTRY RANGES

Trace Elements, ppm									
Cu	Al	Fe	Ni	Si	Mg	C	O	N	H
5-50	8-40	30-150	10-50	10-100	1-10	10-50	15-40	8-40	4-18

Depleted uranium has been alloyed with a variety of elements, including aluminum, zirconium, titanium, columbium, molybdenum, and chromium. Such uranium alloys can be shaped into useful products by casting or by metalworking. A current example of such processing is the U-0.75 Ti uranium-alloy penetrator produced for U.S. Air Force armament requirements.⁽³⁾ In this application, casting trials showed that sound penetrator blanks could be produced economically by investment casting.⁽⁴⁾ Also, the technical feasibility for permanent mold casting, and the production feasibility for making DU penetrators by extrusion forging was established using equipment, tooling, and procedures amenable to high-speed production.⁽⁵⁾

THE METAL URANIUM*

BEHAVIOR AND PROPERTIES

Unalloyed uranium is a very dense metal,⁽⁶⁾ Its density 18.70 gm/cc is nearly equivalent to that of tungsten. It has a metallic lustre approximating a dull silvery hue when freshly prepared, but readily

* The name uranium as used in this report refers to either natural or depleted uranium since no important differences exist in their metallurgical or fabrication properties.

oxidizes in air. It is attacked by cold water. Acids dissolve uranium; however, it is unaffected by alkalis.

Unalloyed uranium can exist in three different allotropic forms whose properties are reviewed in Table 3. Alpha uranium is the base-centered orthorhombic phase which exists below 668 C. Beta uranium is a tetragonal phase which exists between 668 C and 775 C. The gamma phase exists as a body centered cubic crystal structure between 775 and 1132 C, the melting point.

This allotropic behavior results in a variety of microstructural and strength conditions depending on how the metal is processed. For example, alpha uranium is slightly softer than steel, and as such, is considered to be malleable, ductile, and slightly paramagnetic. Its ultimate tensile strength can be increased by cold working; however, this treatment is likely to induce preferred orientation.⁽⁷⁾

Uranium Allotropes

The various allotropes of uranium exhibit widely different properties.⁽⁷⁾ Alpha uranium is reasonably soft and plastic, particularly above 300 C. Because of this behavior, many fabrication operations are done between 300 and 650 C. Uranium and its alloys are susceptible to embrittlement by hydrogen and hydride formation.⁽⁷⁾ At temperatures above 300 C, ductility is greatly improved and appears to result from lower sensitivity to the hydride as well as high mobility of free hydrogen.⁽⁷⁾ If the temperature increases to values between 668 and 775 C, the beta range, the metal becomes significantly harder and brittle. At higher temperatures above 775 C (gamma phase), the metal becomes weak and ductile. Although amenable to metalworking, gamma phase metal is extremely soft thus dimensional control and straightness are difficult to maintain during processing. This strength and ductility behavior within the temperature ranges involved are illustrated in the following tabulation.⁽⁷⁾

Temperature, C	Allotropic State	Tensile Strength, psi	Elongation, percent
RT	Alpha	66,000	4
660	Alpha	6,600	50
670	Beta	15,400	< 1.0
780	Gamma	< 2,200	50

Anisotropy

Although alpha uranium is relatively soft, its properties become complicated by pronounced anisotropy, and this directionality depends on prior fabrication and heat treatment.⁽⁷⁾ Directionality can be removed by betaquenching, heating the metal above 668 C to form the beta phase, and then quenching through the alpha-beta transformation range. This treatment produces a randomly oriented, fine-grain alpha-prime (martensitic alpha) phase. Parts with heavy sections usually require that some alloying element be added to the uranium to stabilize the beta phase during quenching.

TABLE 3. PROPERTIES OF THE CRYSTALLINE FORMS OF URANIUM⁽¹⁾

Property	Alpha Phase	Beta Phase	Gamma Phase
Stability, C	Below 568	668 to 775	775 to 1132 (mp)
Stability, F	Below 1224	1224 to 1422	1422 to 2070
Crystalline form	Orthorhombic	Tetragonal	Body-centered cubic
Cell dimensions, A (at)	(20 C)	(720 C)	(805 C)
a_0	2.585	19.76	3.524
b_0	5.877	—	—
c_0	4.955	5.656	—
Density (calc.), g/cm ³	19.00	18.11	18.06
General characteristics	Soft and ductile	Hard and brittle	Very soft
Young's Modulus, psi (Average value)	25 x 10 ⁶		
Poisson's Ratio (Average value)	0.20		
Coefficient Thermal Expansion, in./in./C (Average value)	19 x 10 ⁶		
Thermal Conductivity, cal/cm/cm ² /sec/C (Average value)	0.064		

Vanadium and niobium, chromium and molybdenum accomplish such stabilization of beta relative to alpha, and are also capable of retaining the beta phase during quenching.

Grain growth and preferred orientation are also related in uranium. Grain growth is extremely sensitive to orientation, to differences in metal purity, and to heat treatments that affect the dispersion of a second phase. If the inclusions are finely dispersed they will have a much greater inhibiting effect on grain-boundary movement than the same amount of material present as relatively large inclusions. Small amounts of aluminum, iron, or silicon additions produce grain refining effects. Recrystallization and grain growth occurring repetitively during thermal cycling can cause gross microstructural changes.

Cast uranium does not exhibit significant preferred effects of anisotropy because of its randomly oriented cast grains. Although its grain size may be large, cast uranium does not exhibit gross macroscopic changes in dimensions after thermal cycling.

Mechanical Properties

The preferred orientation resulting from working alpha uranium produces directionality of its mechanical properties.⁽⁷⁾ For example, a yield stress of 132,000 psi was determined parallel to the rolling direction of sheet, but only 99,000 psi at 45 degrees. Cast uranium, on the other hand, exhibited a tensile strength of 66,000 psi with 4 percent elongation, but did not show directionality.⁽⁷⁾

Uranium rapidly loses strength at elevated temperatures as shown by typical tensile data given in Table 4. Other large differences exist in the properties of cast, wrought, and annealed uranium.⁽⁸⁾

Effect of Impurities. The mechanical properties of uranium are very dependent on the impurity content of the metal. Small amounts of carbon, iron, silicon, or aluminum increase hardness and ultimate tensile strength. Thus, 99.95 percent uranium has exhibited a tensile strength of 58 ksi, while less pure uranium (99.9) exhibited 69 ksi.⁽⁷⁾ In applications for DU where minimum structural requirements are necessary, "doping" with approximately 0.50 percent molybdenum has become standard practice to provide higher and more consistent strength properties.

Proportional Limit. The proportional limit of pure uranium is very low at room temperature (approximately 4 ksi) and falls still lower as the testing temperature increases. Dynamic measurements are complicated by anisotropy. Room-temperature values of 15.8 to 30.0×10^6 psi have been given in the literature for Young's Modulus with averages of around 25×10^6 psi.⁽⁷⁾

Creep Properties

The creep properties of uranium can vary widely depending on metal purity, mechanical working and heat-treatment history, and testing method employed. Also, the stress system during creep can change locally within the test piece because of anisotropic thermal expansion. Hence, rigid control of test temperature is necessary to minimize thermally induced stresses. Thermal cycling superimposed on the creep process not only accelerates creep rate, but also can cause growth in uranium.⁽⁸⁾

TABLE 4. TENSILE PROPERTIES OF ROLLED AND CAST URANIUM⁽⁸⁾

Fabrication Process	Annealing Treatment ^(a)	Test Temperature, C	Ultimate Tensile Strength, ksi	Yield Strength, ^(b) ksi	Percent Elongation
300 C Rolled	β	20	64	24.5	8.5
300 C Rolled	α	20	111	43	6.8
300 C Rolled	α	300	35	17.5	43
300 C Rolled	α	500	11.1	5.1	61.0
300 C Rolled	β	500	10.5	7.1	44
600 C Rolled	β	20	62	25	6.0
600 C Rolled	α	20	88.5	26	13.5
600 C Rolled	α	300	32.0	19	43
600 C Rolled	β	300	27.0	15.5	33
600 C Rolled	α	500	10.5	5.5	57
550 C Rolled	None	20	96.3	30.9	11
As-Cast	None	20	67.2	28.0	4.0

(a) α = alpha-anneal (12 hours at 600 C, slow cool).

β = beta-anneal (12 hours at 700 C, slow cool).

(b) All specimens were standard 0.505-inch rounds.

Grain-boundary effects on the creep mechanism also increase with increasing temperature, and may become dominant above 350 C. Consequently, fine-grained uranium may exhibit poorer creep resistance at higher temperatures than otherwise similar but coarse-grained material.⁽⁸⁾

Corrosion

Uranium, in general, exhibits poor and sometimes unusual corrosion behavior.⁽⁶⁾ For example, an incubation period may or may not precede the actual corrosion reaction, and it may be quite long. Also, relatively minor factors in metal quality and/or corrosion environment may exert considerable influence on observed corrosion rates.

Uranium usually appears black because of an oxide coating. Exposure of a freshly prepared surface to room air for only a few minutes causes the surface to become straw-colored because of the interference effects from the thin, protective oxide film. This film eventually darkens to a blue-black as it thickens, and ceases to become protective.

Bulk uranium metal reacts at room temperature with air, oxygen, hydrogen, water (liquid or vapor), and, of course, the more active substances. In electrochemical activity, uranium ranks close to aluminum.

Hydrogen. Hydrogen is particularly insidious to uranium. Because uranium usually has an oxide film, the attack by hydrogen is generally delayed by an incubation period. During this period, hydrogen diffuses to an active site within the oxide coating and enters the metal, which has low solubility for hydrogen at ambient temperatures. The uranium hydride (UH_3) formed is unstable in air (O_2) and, accordingly, can react to form UO_2 and water. Uranium, being unstable in water, forms UO_2 and hydrogen, which is usually the source of hydrogen. The results of hydrogen absorption in uranium parts are low to nil ductility and delayed cracking during shipment or while in service. Deoxygenated environments promote hydrogen absorption and impaired ductility.

Water. Uranium reacts with water, liquid or vapor, to form UO_2 and hydrogen. As the UO_2 protective film thickens, it becomes unstable and breaks down at local points. The black powdery UO_2 spreads gradually until the entire surface is covered. The rate of attack is not influenced significantly by impurities in the water. However, the rate of corrosion is influenced by the amount of impurities in the metal and their distribution and orientation. After an initial period during which the attack is general, accelerated attack occurs at local areas resulting in pits and craters apparently from localized galvanic attack.

Uranium should be stored in air of no more than moderate humidity - with free access of air to all surfaces.

Other Gases. No appreciable attack of uranium occurs in dry atmospheres of helium, argon, carbon monoxide, carbon dioxide, and hydrocarbon gases at temperatures up to 500 C. However, relatively slight amounts of water vapor in any of these gases can cause extensive corrosion. Thus, uranium corrodes more rapidly in commercial gases because of the moisture present. Such gases must be thoroughly dried before being used as atmospheres.

Molten Baths. Uranium has been heated in molten lead for 50 hours at 350 C without appreciable reaction.⁽⁶⁾ Longer periods and/or higher temperatures (800 to 1000 C), however, have caused the uranium to be completely penetrated. Molten salts are often used for heat treating uranium. Table 5 shows the corrosion results for six heat-treating mixtures of salts.

CONCLUDING REMARKS

Because of the wide variation in mechanical properties of uranium with purity, temperature, and previous thermal-mechanical history, no attempt has been made to quote data on any more than a semiquantitative basis. Such an approach is sufficient to illustrate general principles. For more accurate data the reader should refer to original work or to appropriate reviews where quantitative properties are recorded together with the corresponding conditions.⁽⁸⁾

TABLE 5. CORROSION OF URANIUM IN MOLTEN SALTS AT 593 C⁽⁶⁾

	Time, hours	Observed Attack
44Na ₂ CO ₃ -30K ₂ CO ₃ -26Li ₂ CO ₃	½ to 2	No corrosion
	4	Surface pitting
74K ₂ CO ₃ -26Li ₂ CO ₃	½ to 2	No corrosion
	4	Pitted
47Na ₂ CO ₃ -32K ₂ CO ₃ -21Li ₂ CO ₃	½ to 2	No corrosion
	2	Pits beginning
	4	Badly pitted
53K ₂ CO ₃ -46.6Li ₂ CO ₃	½ to 1	No corrosion
	2	Surface pits
20NaOH-30K ₂ CO ₃ -50Na ₂ CO ₃	½ to 4	Surface etching
47Na ₂ CO ₃ -47K ₂ CO ₃ -6Li ₂ CO ₃	½	Scaling, 0.24% weight loss
	2	Scaling, 1.0% weight loss
	4	Scaling, 1.2% weight loss

URANIUM ALLOYS

ALLOY SYSTEMS AND PROPERTIES

Alloying additions to depleted uranium, even in relatively small quantities, increase the yield and tensile strengths and narrow the range of these strengths when compared with depleted uranium. In addition, such alloying reduces the susceptibility of uranium to embrittlement by hydrogen and improves corrosion resistance.^(7,8) On the other hand, uranium itself is not extensively used as an alloying agent. Although considerable work had been performed on the use of DU as an alloying addition to steels and other alloys, the results of these efforts were largely unsuccessful.⁽⁹⁾

In recent years, commercial and military applications of uranium-base alloys have been based on the density of these alloys for radiation shielding, counterweights, inertial-systems components and penetrators.⁽¹⁰⁾ Alloying was used to meet the structural requirements, and to improve the generally poor corrosion resistance of unalloyed uranium. This alloying had been based on lean binary to quaternary alloys which, in general, are for special-purpose extensions of the properties of DU. An excellent compendium of recent developments in the physical metallurgy of uranium and its alloys has been published.⁽¹¹⁾ This publication is indicative of the current progress in processing and physical metallurgy of uranium alloys and is the basis for a large part of the following discussion on these materials.

In uranium-base alloys, strengthening by alloying is usually achieved by solid solution, martensitic-transformation, and precipitation-hardening mechanisms. In many respects, alloying in the U-Metal binary and higher order systems is very similar to the iron-carbon metastable phase system. These similarities include the effects of additions on stabilizing gamma, promoting age hardening through the precipitation of an intermetallic in a quenched martensitic structure, and the general time-temperature-transformation behavior. Important binary systems representing this behavior are U-Mo, U-Ti, and U-Zr, which are briefly reviewed in the following. Two polynary alloy systems called "Quad" and "Quint" are also described.

U-Mo System

The metastable gamma phase of the U-Mo system is the most sluggish of the binary alloys to transform. Accordingly, alloys representing this system can be considered for use in the metastable condition. The U-Mo constitutional diagram⁽¹²⁾ is shown in Figure 1. The alpha and alpha-prime structures characterize these alloys up to about 5 percent molybdenum. Above 5 percent, and up to the limits of the gamma solid solution, the gamma phase becomes metastable.

The TTT diagrams representing the beginning of the alpha-to-gamma transformation for four uranium-molybdenum alloys are shown in Figure 2. The transformation times increase with alloy content up to about 12 percent molybdenum.⁽⁸⁾

Very high strengths can be achieved by means of the martensite-type transformation in the U-Mo system. The greatest strength of the 2 weight percent molybdenum alloy is achieved by quenching from the gamma phase (700 C) and then aging two (2) hours at 400 C. With these heat treatments 0.2 percent offset yield strengths as high as 226,000 to 248,000 psi have been obtained in the alloy in compression at room temperature. Unfortunately the high strength of these alpha-prime materials could be lost during extended service at high temperatures due to overaging.⁽⁸⁾

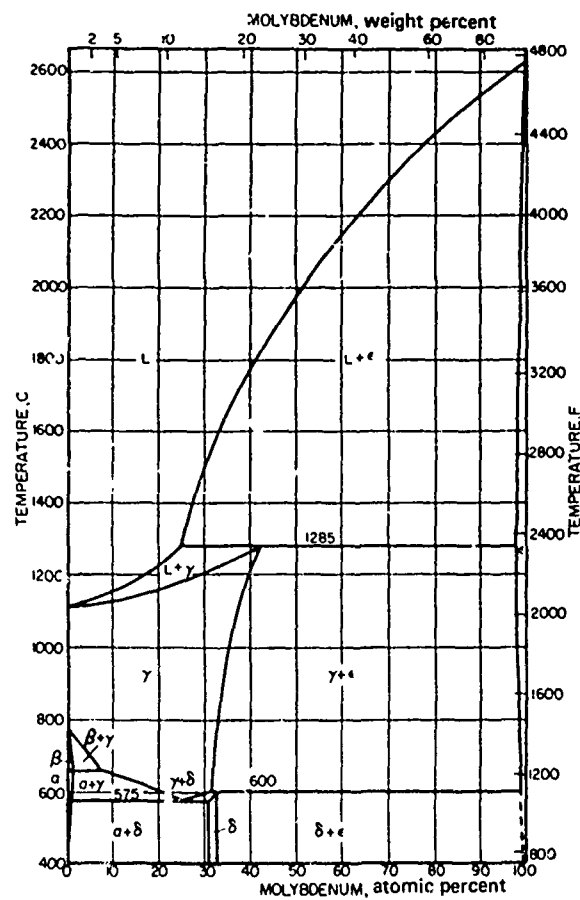


FIGURE 1. THE URANIUM-MOLYBDENUM CONSTITUTIONAL DIAGRAM⁽¹²⁾

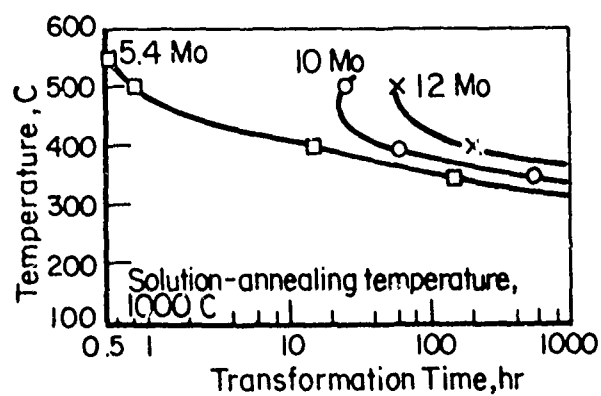


FIGURE 2. TTT DIAGRAMS FOR URANIUM-MOLYBDENUM ALLOYS

It appears that, upon quenching, the ductile and soft gamma phase of uranium cannot be retained for those U-Mo alloys containing less than 7 percent molybdenum. However, the proportion of gamma retained (by quenching after solution heat treatment) increases as the molybdenum content increases. At 7 percent molybdenum, gamma is completely retained upon quenching, which produces the good ductility of these alloys. In general, the ductility is strongly influenced by impurities -- particularly hydrogen. Also, molybdenum in substitutional solid solution greatly strengthens the body-centered cubic structure of gamma uranium.⁽⁸⁾

Table 6 presents the high-temperature tensile properties of a 12 percent molybdenum alloy after the following three different heat treatments: (a) solution heat treatment at 900 C alone and after subsequent aging at 500 C for (b) three hours and (c) forty hours.

Creep data at 815 C for a series of U-Mo alloys are shown in Table 7. The best results for these alloys were obtained with a 13.3 Mo alloy.

U-Ti System

Unlike the uranium-molybdenum alloys, the gamma phase of uranium-titanium alloys transform readily.⁽⁸⁾ The constitutional diagram of the U-Ti system is shown in Figure 3. Data on mechanical properties for some lean alloys are given in Table 8. Creep data at 815 C are shown in Table 9 for alloys rich in titanium. Near maximum results in creep were achieved over a range of composition from U-32 Ti to U-55 Ti. This range of composition brackets the titanium-rich gamma eutectoid which occurs at about 34 weight percent titanium.

In recent years, considerable research has been performed on lean U-Ti alloys, particularly the U-0.75 Ti composition. The heat treatments, resulting microstructures, and mechanical properties of titanium and other alloys have recently been extensively evaluated.^(10,13,14) Eckelmeyer⁽¹³⁾ found that the optimum elongation for specific values of yield strength were obtained in the underaged condition for U-3/4 Ti and U-4 1/2 Nb and in the overaged condition for U-2 percent Mo. Room-temperature tensile properties for these alloys are shown in Table 10 and the aging response of the U-0.75 Ti alloy is shown in Figure 4.⁽¹³⁾ However, it should be recognized that relatively small variations in the nominal Ti concentration will have a significant effect on hardness⁽¹⁰⁾, and variations in aging response may occur in extruded rod produced from billet of the same nominal chemistry, but from different vendors and, consequently, different melting practices.⁽³⁾

Ammons⁽¹⁴⁾ evaluated the effects of homogenization treatments on the mechanical properties of as-cast U-0.75 Ti, the residual stresses in quenched cylinders, and the general aging response of this alloy. As shown by the results in Table 11, homogenization treatments produced a significant improvement in the room-temperature ductility of the as-cast and heat-treated alloy.⁽¹⁴⁾ All the data in this table were obtained after the indicated homogenization treatments, and after solution treatment at 800 C for 1 hour and water quench, and aging at 380 C for 6 hours. The utility of the homogenization treatments was determined by electron microprobe analyses on a 150 mm square analyzed with a 30 x 30, 900 point grid. The as-cast material contained titanium gradients ranging from a low 0.1 to 0.2 percent to as high as 3.0 percent. The finding that the average titanium concentration decreased from 0.85 percent in the as-cast material to 0.69 after 1 hour at 1000 C while the observed inclusions increased, indicated that the improved ductility could have been associated with the removal of carbon and silicon from the matrix by coarsening of the inclusions.

TABLE 6. TENSILE PROPERTIES OF URANIUM-12 WEIGHT PERCENT MOLYBDENUM ALLOY⁽⁸⁾

Heat Treatment ^(a)	Test Temperature, F	Yield Strength, (b) psi	Tensile Strength, psi	Elongation Percent ^(c)		Reduction in Area, percent
				Uniform	Total	
Process A	500	102,000	104,000	1.8	6.9	50
	600	107,000	108,000	2.3	3.6	23
	700	98,000	102,000	3.0	4.3	33
Processes A + B	600	103,000	104,000	—	5.8	45
	600	114,000	118,000	2.1	5.3	32
	500	114,000	116,000	1.4	5.2	37

(a) Process A: 24 hr 900 C, water quench

Process B: 3 hr age at 500 C

Process C: 40 hr at 500 C.

(b) 0.5 percent offset.

(c) 1-inch gage length.

TABLE 7. CREEP DATA FOR URANIUM-MOLYBDENUM ALLOYS AT 815 C IN VACUUM⁽⁸⁾

Alloy	Carbon Content, percent	Condition ^(a)	Stress, psi	Time for 1% Deformation, hr	Minimum Creep Rate, %/hr	Test Time, hr ^(b)	Percent Elongation
U-4.3 Mo	0.50	A	500	1	2.16	6.9	15.1
U-10 Mo	0.13	A	500	7	0.034	160	4.5
U-10 Mo	0.13	A	500	2	0.052	166	7.5
U-29 Mo	0.24	B	500	29	0.014	172	3.6
U-12 Mo	0.10	C	500	>330 ^(c)	0.00008 ^(c)	337 ^(c)	0.1 ^(c)
U-12 Mo	0.27	C	500	150	0.0023	191	1.1

(a) Condition A: Induction melted, cast in graphite, rolled at 1650 F.

Condition B: Induction melted, cast in graphite, canned, and rolled at 2200 F.

Condition C: Induction melted, cast in graphite, canned, and rolled at 2200 F.

(b) All tests were discontinued before rupture.

(c) Stress subsequently raised in successive steps above 500 psi.

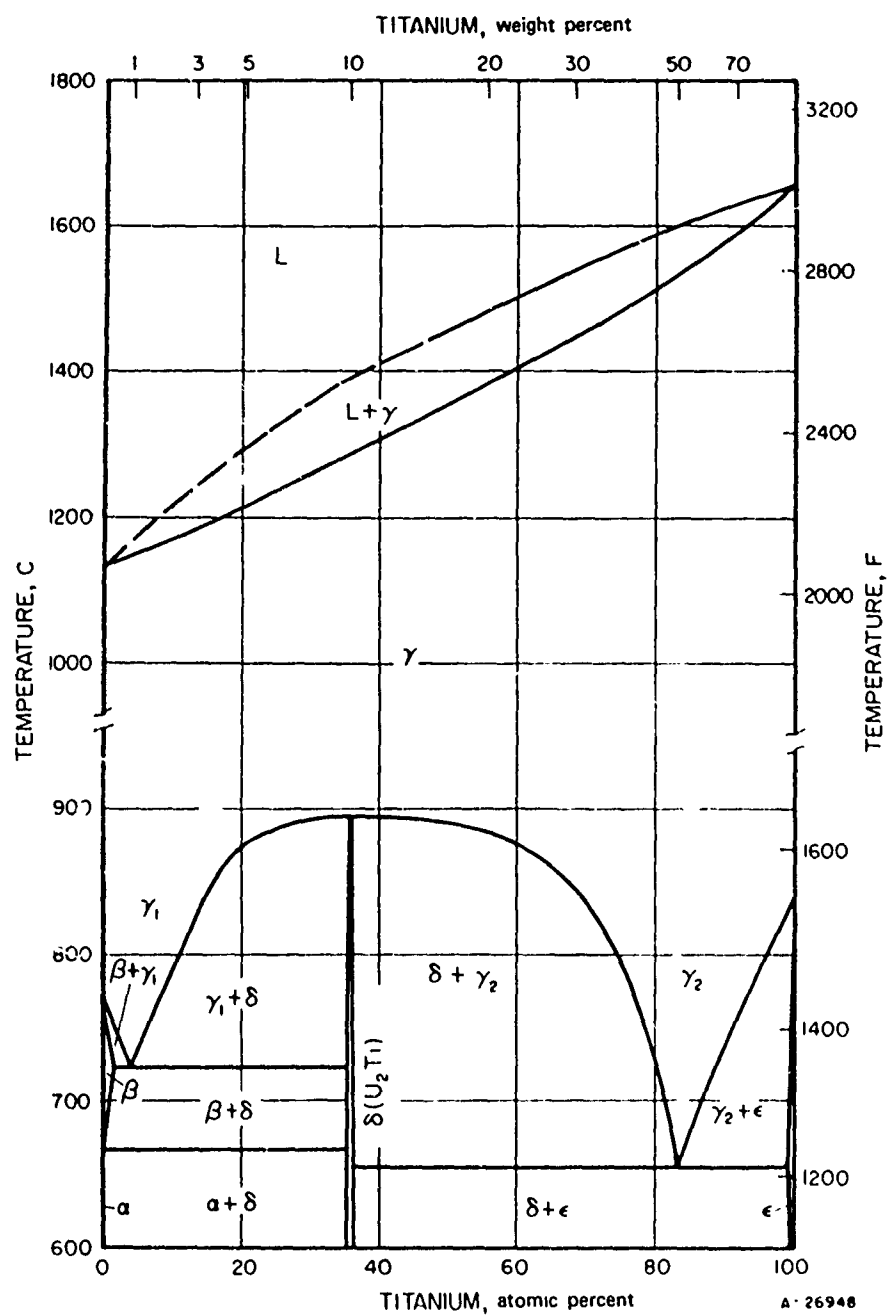


FIGURE 3. THE URANIUM-TITANIUM CONSTITUTIONAL DIAGRAM⁽⁴⁾

TABLE 8. MECHANICAL PROPERTIES OF URANIUM-TITANIUM ALLOYS(8)

Titanium, weight percent	Heat Treatment and History	Test Temp., C	0.2% Offset Yield Strength, 1000 psi	Tensile Strength, 1000 psi	Modulus of Elasticity, 10 ⁶ psi	Percent Elongation	Reduction of Area, percent	Hardness, DPN
0.1		6		78.1		4.9	4.3	
		25	34.0	82.4		5.7	5.7	198-226
		38		86.1		7.7	9.5	
		53		90.6		11.2	10.0	
		80		88.9		12.9	12.5	
		106		86.4		22.3	18.4	130-251
		150		77.5		26.2	21.7	
		300						112-130
		400						90
		500	19.0	25.2		20.5	62.8	65
		725						35
0.53	As cast	R. T.	55.0	100.0	22	3.9	4.0	305
0.95	As cast	R. T.	75.0	115.0	26	2.5		340
	4 hr at 800 C, W.Q.	R. T.	92.0	194.0	21	17.0	15.0	425

TABLE 9. CREEP DATA FOR URANIUM-TITANIUM ALLOYS AT 815 C IN VACUUM⁽⁸⁾

Alloy	Carbon Content, %	Condition (a)	Stress, psi	Time for 1% Deformation, hr	Minimum Creep Rate, %/hr	Test Time, hr(b)	Percent Elongation
U-12.1 Ti	0.38	A	500	0.7	0.14	30.9	6.4
U-6.3 Ti	0.10	B	500	0.04	28	0.4	11.0
U-20 Ti	0.22	A	500	3.0	0.05	78	4.6
U-20 Ti	0.25	C	500	8.5	0.06	170.4	12.8
U-32 Ti	0.27	C	500	35	0.0034	211	2.6
U-20 Ti	0.45	A	500	23	0.008	149.5	2.9
U-25.5 Ti	1.00	A	500	163	0.003	238.6	1.4
U-30 Ti	0.80	A	500	40	0.0045	167.7	2.2
U-32 Ti	0.32	A	500	44	0.0032	197	2.1
U-50 Ti	1.64	A	500	9.5	0.06	111.8	7.4
U-55 Ti	0.19	D	500	12.5	0.007	193	3.7
U-65 Ti	0.95	D	500	10.5	0.017	116	3.7
U-75 Ti	0.49	D	500	< 0.1	12.0	1.1	12.2
U-90 Ti	0.28	D	500	1.7	0.4	44.7	9.4

(a) Condition A: Induction melted, cast in graphite, rolled at 1800 F.

Condition B: Double induction melted, cast in copper mold, rolled at 1500 F.

Condition C: Induction melted, cast in graphite, rolled at 1500 F.

Condition D: Arc melted, remelted in BeO, forged, and rolled at 1700 F.

(b) Test discontinued before rupture.

TABLE 10. ROOM-TEMPERATURE TENSILE PROPERTIES OF SOME
BINARY URANIUM ALLOYS⁽¹³⁾

Condition	Yield Strength, MN/m ²	Ultimate Strength, MN/m ²	Percent Elongation
U-0.75 Ti			
Underaged	700	1350	14
	850	1450	13
	1000	1525	7-½
Peak Strength	1200	1650	2-½
Overaged	1000	1450	3
	850	1300	4
	700	1175	7
U-2 Mo			
Underaged	700	1150	4
	850	1200	4
	1000	1250	2-½
	1150	1350	1-½
Peak Strength	1350	1600	1-½
Overaged	1150	1375	1-½
	1000	1400	3-½
	850	1225	8
	700	1125	17
	550	925	24
U-4½ Nb			
Underaged	400	1075	16
	600	1075	16
	800	1150	13
	1000	1275	10
	1200	1325	4
Peak Strength	1400	1400	1
Overaged	1200	1200	< 1
	1000	1150	< 1
	1800	1150	1

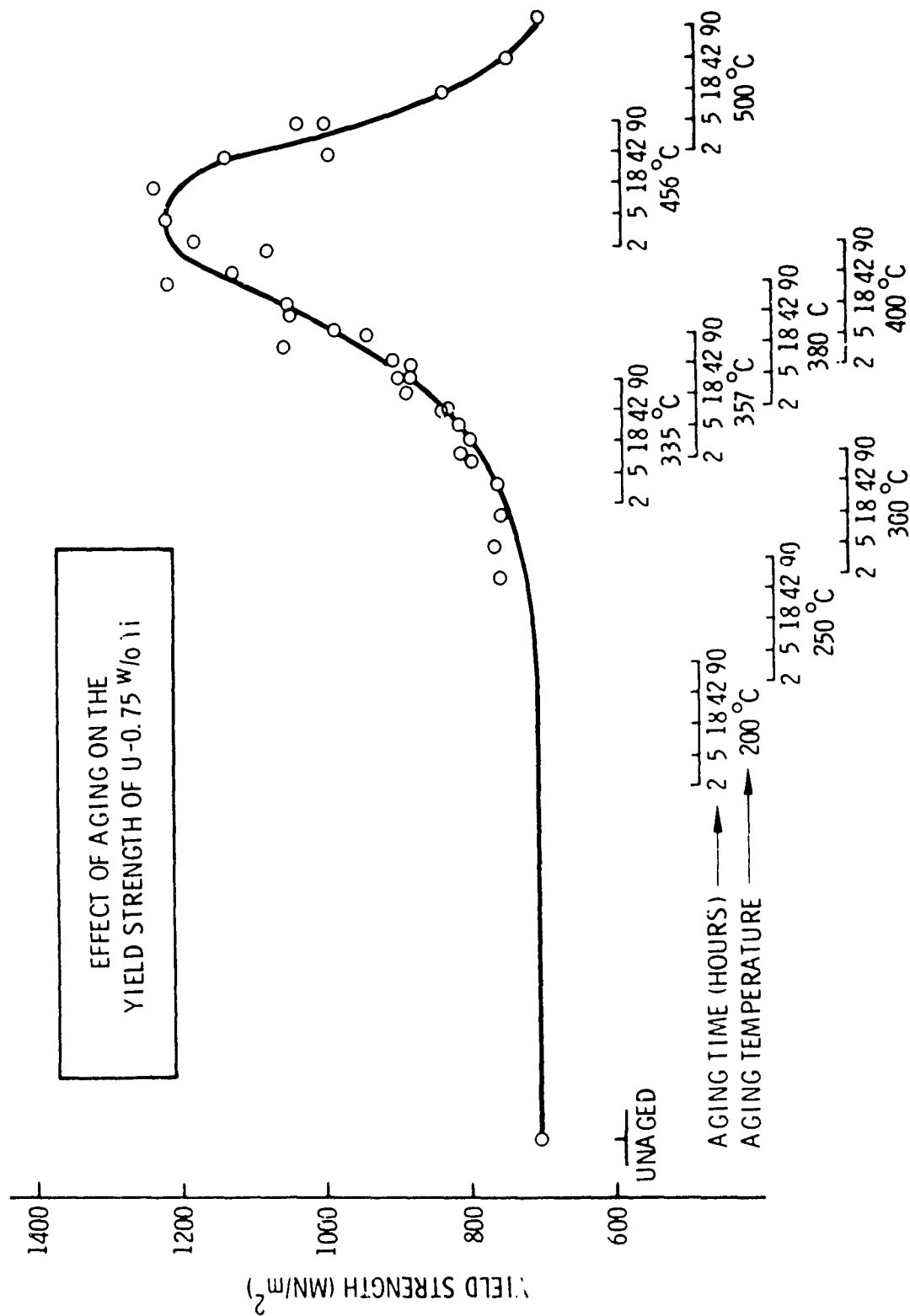


FIGURE 4. AGING BEHAVIOR OF U-0.75 W₁₀11i

TABLE 11. MECHANICAL PROPERTIES OF CAST U-0.75 TI AFTER VARIOUS
HOMOGENIZATION TREATMENTS⁽¹⁴⁾

Condition	Tensile Strength ksi	Yield Strength (0.2%) ksi	Yield Strength (0.35% Strain) ksi	Percent Elongation in 1 inch	Percent Reduction in Area
As Cast	115.9±2.8	72.2±1.4	83.7±1.3	2.8±0.3	1.8±0.4
Not Homogenized	206.2±4.2	142.4±5.2	143.8±3.5	4.7±1.7	4.6±1.0
Homogenized 2 hr at 800 C	185.3±5.3	115.2±4.0	123.0±3.2	8.8±2.1	8.6±1.2
Homogenized 24 hr at 800 C	197.1±3.4	128.3±4.4	131.5±3.4	8.4±1.4	8.7±1.8
Homogenized 2 hr at 1000 C	207.4±3.3	132.2±2.7	134.0±2.2	13.3±1.6	13.7±2.5
Homogenized 24 hr at 1000 C	204.6±3.3	126.4±3.6	131.1±3.1	16.7±2.0	18.0±4.2

The effects of hydrogen on ductility after the homogenization treatments were not considered by Ammons although the hydrogen contents were measured after various homogenization treatments. Tensile blanks approximately ½-inch square by 3-inches long were either as-cast with approximately 3-ppm hydrogen or rolled from a salt (composition not specified) bath with approximately 30-ppm hydrogen. After the 1 hour treatments of the wrought material at 750, 850, and 950 C, the hydrogen levels were 3.06, 0.88, and 0.49 ppm, respectively. The average hydrogen levels after annealing in vacuum at 750, 850, and 950 C were 0.07 and 0.03 ppm after 1 and 4 hour treatments, respectively, for the as-cast material and 0.06 ppm after the 4 hour treatment for the wrought material. These observations demonstrate the general finding with uranium and its alloys that salt-bath heat treatment will introduce hydrogen, and vacuum heat treatment, usually above 800 C, will remove hydrogen.

Powell and Condon evaluated the effects of hydrogen concentration on the ductility and delayed failure of uranium alloys.⁽¹⁵⁾ Figures 5 and 6 demonstrate the effects of hydrogen on the ductility of the U-0.75 Ti and U-8.5 Nb alloys. The response of the titanium alloy approaches that of pure uranium. In general, the hydrogen content to achieve the minimum ductility increases with alloy content. Clearly, the effects of homogenization treatments on the ductility of the U-0.75 Ti must also consider the effects of the homogenization treatment on the hydrogen content, and its precipitous effect on ductility at hydrogen concentrations below about 1 ppm, the approximate solubility limit of hydrogen in this alloy.

Quenching from the gamma-phase region has been known to introduce voids and cracks in uranium alloys from the generation of high residual stresses due to the thermal diffusivity, the resulting transformation products, and the product shape.⁽¹⁴⁾ Javorsky studied the quench-rate sensitivity of 0.875-inch-diameter by 0.845-inch-long specimens and found that most quenching media would provide the same aging response at 350 C, and that quenching rates in conventional soluble oil below about 40 C sec⁻¹ would avoid the occurrence of the centerline defect.⁽¹⁶⁾

U-Zr System

The uranium-zirconium alloys represent the third alloy system where the degree of solid solubility in the gamma phase is extensive, and where very high strengths are possible by means of a martensite-type transformation. For example, binary alloys of 5 to 10 weight percent zirconium when gamma-quenched form a martensitic alpha-like structure (alpha prime) in which virtually all of the zirconium remains in metastable solid solution. The alpha-prime structure is very hard and strong in the quenched condition. By varying the tempering conditions to control the precipitation of the excess solute from solid solution, a whole range of properties can be obtained. The hardness data in Table 12 illustrate the vastly different properties obtained when uranium-5 weight percent zirconium alloy is treated in this manner.

The tensile properties at 370 C for a series of uranium-zirconium alloys are shown in Table 13. These samples were hot worked and heat treated 24 hours at 575 C and furnace-cooled. The maximum strength was attained at about 20 weight percent zirconium. At higher temperatures, namely, in the gamma-phase region, the maximum strength may occur at a higher zirconium composition.

Creep data for a series of uranium-zirconium alloys are shown in Table 14. The best results were obtained with U-46.5 Zr, which is in the gamma phase at 815 C and near the composition of the gamma eutectoid.

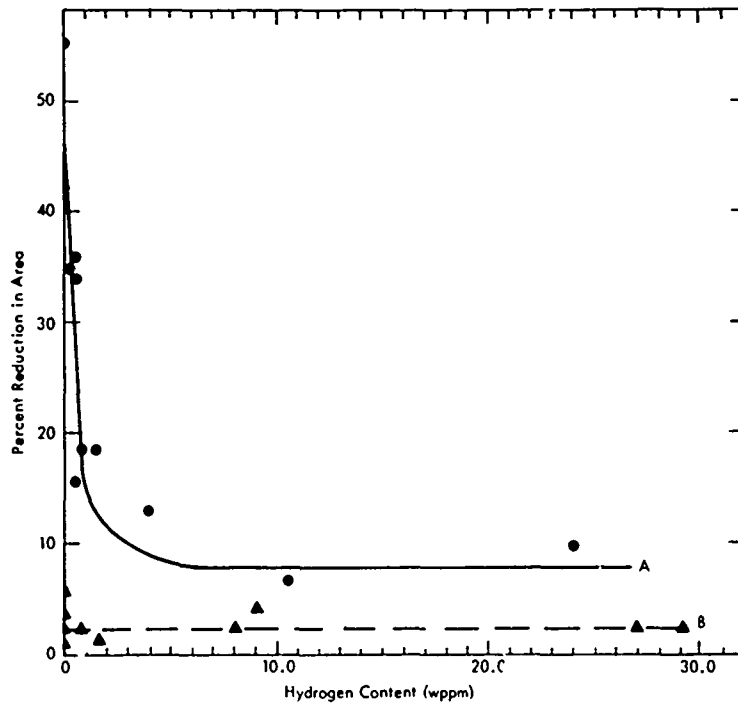


FIGURE 5. SMOOTH TENSILE TEST RESULTS FOR U-0.75 Ti⁽¹⁵⁾

Curve A Gamma-quenched-yield strength at 0.2% offset, 92 ± 2 ksi

Curve B Gamma-quenched and aged at 400 ± 1 C for six hours; Yield strength at 0.2% offset - 146 ± 9 ksi

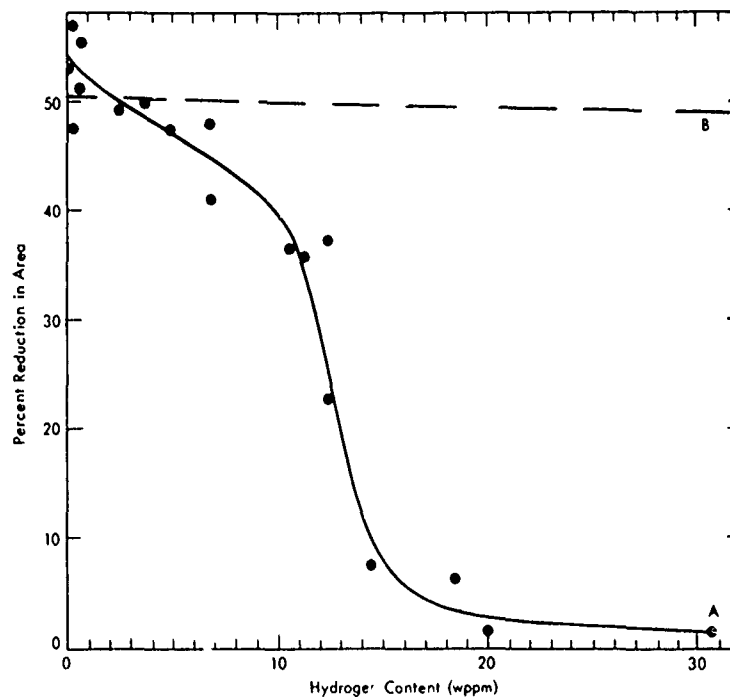


FIGURE 6. SMOOTH TENSILE TEST RESULTS FOR GAMMA-STABILIZED URANIUM ALLOYS⁽¹⁵⁾

Curve A Gamma-quenched uranium-8.5% niobium alloy; Yield strength at 0.2% offset - 88 ± 7 ksi

Curve B Gamma-quenched uranium-7.5% niobium-2.5% zirconium alloy; Yield strength at 0.2% offset - 74 ± 9 ksi

TABLE 12. VICKERS HARDNESS OF URANIUM-5 WEIGHT PERCENT ZIRCONIUM ALLOY⁽⁸⁾

Heat Treatment	Hardness ^(a)
1 hr 900 C, water quenched	535
1 hr 900 C, water quenched, 2 hr 200 C, water quenched	520
1 hr 900 C, water quenched, 2 hr 300 C, water quenched	512
1 hr 900 C, water quenched, 2 hr 400 C, water quenched	545
1 hr 900 C, water quenched, 2 hr 500 C, water quenched	475
1 hr 900 C, water quenched, 2 hr 575 C, water quenched	375
1 hr 900 C, water quenched, 2 hr 650 C, water quenched	315

(a) Obtained with 30-kg load.

TABLE 13. TENSILE PROPERTIES OF ARC-MELTED URANIUM-ZIRCONIUM ALLOYS AT 370 C⁽⁸⁾

Zirconium Content, weight percent	Yield Strength, ^(a) psi	Tensile Strength, psi	Percent Elongation ^(b)	Percent Reduction in Area
0	21,300	31,400	27.0	57.0
2.4	35,100	48,400	17.0	49.0
5.5	50,500	77,000	10.0	25.0
11.5	100,800	122,800	8.0	29.0
20.5	124,000	135,200	8.0	18.0
31.4	112,000	145,200	7.0	7.0
41.7	97,000	115,300	8.0	13.0
50.5	68,100	96,100	22.0	28.0

(a) 0.2 offset.

(b) 2-inch gage length.

2

TABLE 14. CREEP DATA FOR URANIUM-ZIRCONIUM ALLOYS AT 815 C IN VACUUM⁽⁸⁾

Alloy (a)	Condition (b)	Stress, psi	Time for 1% Deformation, hr	Minimum Creep Rate, %/hr	Test Time, hr (c)	Percent Elongation
U-5.0 Zr	A	500	0.8	0.65	6.0	8.1
U-11.3 Zr	A	1422	< 0.1	43	1.0	93.8
U-22.4 Zr	B	500	0.45	1.0	11	14
U-46.5 Zr	B	500	56	0.013	169	15.1
U-72.3 Zr	B	500	40	0.021	162.7	12.3

(a) Carbon 0.07 to 0.08 percent.

(b) Condition A: Induction melted, cast in graphite, rolled at 1550 F.

Condition B: Double arc-melted, jacketed, forged, and rolled at 1450 F.

(c) Test discontinued before rupture.

Polynary Uranium Alloys

Uranium alloys with four or more major elements have been developed for use in high-density structural applications. These alloys exhibit certain phase transformation phenomena and age-hardening reactions from which a relatively wide range of mechanical properties can be derived.⁽¹⁷⁾

Two polynary systems that have been studied are called Quad and Quint. The composition of the Quad system is $U-(K)Mo-(K)Nb-(K)Zr-\frac{1}{2}Ti$ with (K) being the same for all elements. It usually ranges from 3/4 to 2 percent. In a similar manner, the Quint system can be written as $U-(K)Mo-(K)Zr-(K)Nb-\frac{1}{2}V-\frac{1}{2}Ti$.⁽¹⁷⁾

The higher strength levels of these materials are obtained by heating well into the gamma region (1600 to 1650 F), holding for 2 to 3 hours, and then quenching into room-temperature water. The resulting as-solutionized material is in the softest possible condition, but can be age-hardened to specific strength levels by isothermal heating in the age-hardening region (400 to 800 F).⁽¹⁷⁾

Quad alloys can be age-hardened between 400 and 600 F to increase tensile yield strength appreciably without significant loss in ductility. Optimum strength and hardness are achieved by aging at 800 F, but this is accompanied by loss in ductility and impact strength as shown in Table 15.

Rods of Quad alloy in the as-extruded condition can exhibit an exceptionally good combination of tensile strength, tensile ductility, impact strength, and hardness, as shown in Table 16. Extruded rods of a Quint alloy show higher strengths but lower ductilities than those for a corresponding Quad alloy. The data in Table 17 show this behavior.

Corrosion

Alloying, in addition to strengthening, is used to improve the corrosion resistance of uranium. In general, adequate strengthening can be achieved in many binary alloys, but additional alloy ingredients are added to improve the corrosion resistance which depends very strongly on the amount of addition as shown in Figures 7 and 8. These data show the general effects of the composition on the rate of hydrogen production and the rest potential in a 10^{-3} M KCL solution.⁽¹⁸⁾ Heat treatment most significantly affects stress-corrosion behavior, as shown in Figure 9, for the U-0.75 Ti alloy in a 50 ppm Cl^- solution.⁽¹⁹⁾ Two types of stress-corrosion cracking have been observed in uranium alloys -- transgranular and intergranular --, and different mechanisms have been proposed for each.⁽¹⁹⁾ Transgranular cracking has been attributed to the mechanical wedging action of the reaction product and intergranular cracking has been attributed to hydrogen embrittlement. Transgranular cracking is usually observed with precracked test specimens and, for this reason, appears to initiate with greater difficulty than intergranular cracking which is more common. In general, transgranular cracking is observed in all environments with alloys having a low level of additions, whereas in alloys with higher additions this mode is observed only in air tests. Conditions which promote intergranular cracking are high-alloy content and environments containing water and/or chloride ion.

Magnani⁽¹⁹⁾ states that the details of the cracking mechanisms in uranium alloys may not be understood, but some guiding principles can be established for the safe use of these alloys. These principles include the following:

- (1) The susceptibility to stress-corrosion cracking increases as the strength of the alloy increases,

TABLE 15. MECHANICAL PROPERTIES OF QUAD ALLOYS SOLUTIONIZED AND AGED⁽¹⁷⁾

Property	Solutionized and Aged: Temperature, F									
	As Solutionized					600				
K(a)	3/4	1½	2	3/4	1½	2	3/4	1½	2	800
Tensile Yield Stress, 1%, ksi	90.1	45.1	33.6	95	146	130.3	138.5	190	204	155.8
Tensile Strength, ksi	195.8	172.4	136.5	205.4	192.4	178	225.6	240	239.5	272.7
Tensile Elongation, percent	9.0	16.7	12	8.0	12	7.5	5.0	3.0	3.0	2.7
Tensile Reduction in Area, percent	21.8	21.2	25.8	11.6	14.7	27.4	8.0	11.0	14.7	2.0
Hardness, Rockwell C	37	28	10	42	42	38.8	44	50	47	54
Impact Strength V-notch Charpy -40 F ft lb	8.1	10.3	12.4	8.1	6.2	7.2	3.7	4.4	4.7	3.4

(a) K is weight of alloying elements (Mo, Zr, Nb and Ti), same for all elements.

TABLE 16. MECHANICAL PROPERTIES OF AS-EXTRUDED QUAD ALLOYS
(3/4 in.-diameter rod)⁽¹⁷⁾

Property	Value of (K), %			
	3/4	1	1½	2
Tensile Elastic Modulus (millions of psi)	23	21	21	14.8
Tensile Yield Strength, 1% offset, ksi	111	149	227	188
Tensile Strength, ksi	207	247	308	239
Tensile Fracture Strength, ksi	258	318	332	260
Tensile Elongation, percent	10.5	8.2	3.0	3.9
Tensile Reduction Area, percent	16.5	22	8.9	9.2
Impact Strength, V-notch Charpy, -40 F, (ft-lb)	4.2	4.0	3.9	3.3
Hardness, Rockwell C	40	49	55	49

TABLE 17. MECHANICAL PROPERTIES OF URANIUM "QUAD", "QUINT",
AND U-0.75 TI STA ALLOYS

Alloy	Heat	Y.S., ksi		T.S., ksi	Percent Elon.	Percent R.A.	Hardness R _c	Impact Energy, ft-lb
		0.1%	0.2%					
3/4% Cu-U ^(a)	727	93.2	11.5	200.0	16.5	25.4	41.6	4.55
1% Quad ^(b)	728	147.0	169.0	240.0	7.5	17.7	47.8	4.4
1% Quint ^(c)	—	—	236.0	281.4	3.5	4.6	52.0	—
U-3/4Ti(STA) ^(d)	—	156.0	184.7	247.6	1.5	0.9	—	—

(a) U(3/4 Mo, 3/4 Zr, 3/4 Nb, 1/2 Ti).

(b) U(1 Mo, 1 Zr, 1 Nb, 1/2 Ti).

(c) U(1 Mo, 1 Zr, 1 Nb, 1/2 V, 1/2 Ti).

(d) Gamma heat treated at 850 C - 2 hr; water quenched and aged at 450 C - 4 hr.

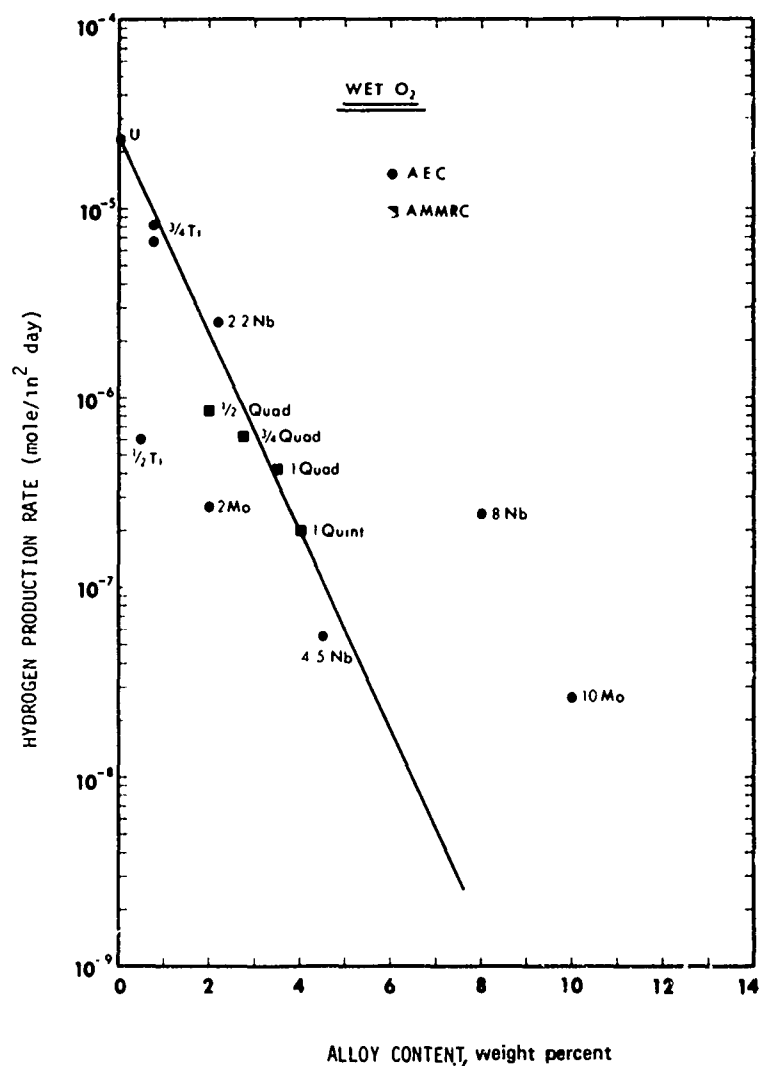


FIGURE 7. RATE OF HYDROGEN PRODUCTION VERSUS TOTAL ALLOYING CONTENT FOR URANIUM ALLOYS IN WET OXYGEN AT 75 C⁽¹⁸⁾

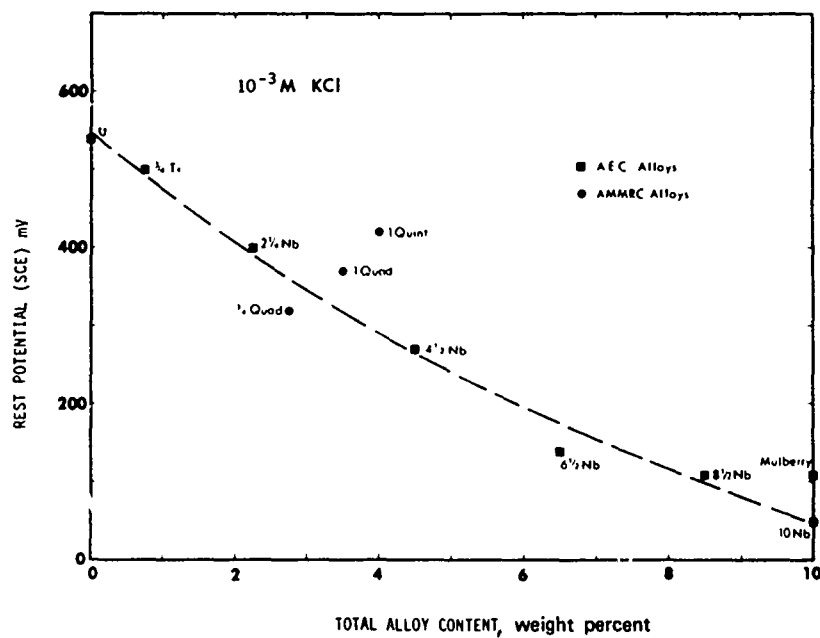


FIGURE 8. REST POTENTIAL (SCE) VERSUS TOTAL ALLOY CONTENT FOR URANIUM ALLOYS IN 10^{-3} M KCL⁽¹⁸⁾

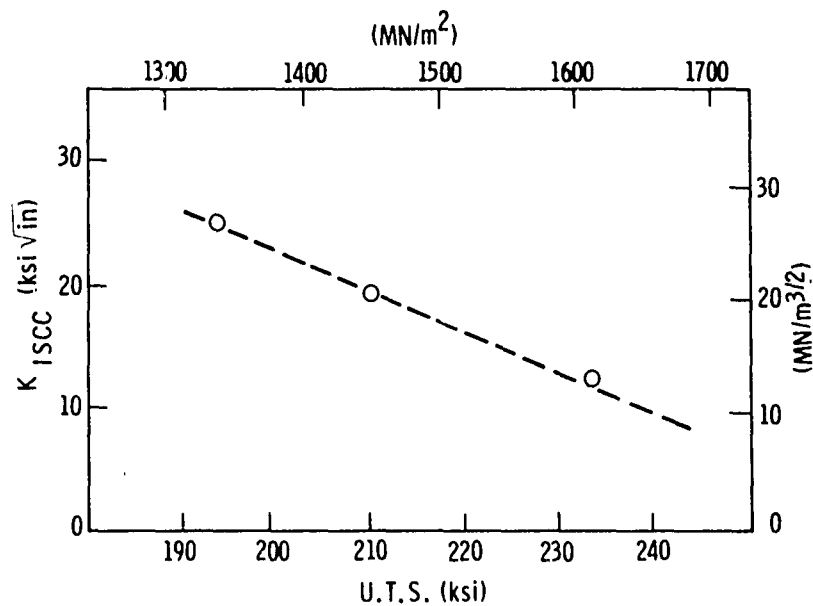


FIGURE 9. PLANE STRAIN THRESHOLD FOR STRESS CORROSION CRACK PROPAGATION FOR U-0.75 TI⁽¹⁸⁾

- (2) The susceptibility to stress-corrosion cracking increases as the general corrosion resistance increases, and
- (3) Significant differences exist between the susceptibility to cracking of smooth and precracked specimens.

Recently, several studies of the corrosion behavior and corrosion protection of uranium alloys have been published. Much of this work has been excellently reviewed and analyzed to establish general principles.^(18,19) Although the general corrosion behavior of uranium alloys when compared with common construction materials is poor, under certain environments some uranium alloys perform as well as steels and aluminum alloys, and minor alloying additions can significantly affect the corrosion resistance in lean alloys.⁽³⁾ The need for long-term use and/or storage of uranium alloys has also led to recent developments and reviews of protective coatings for uranium alloys.⁽¹⁸⁾

Detailed consideration of alloy composition, environment, heat treatment (which appears to be a second-order effect on general corrosion), etc., and the anticipated response to corrosion can be obtained through review of the cited references.

CONCLUDING REMARKS

Only a few elements alloy with uranium at elevated temperatures to produce a metastable gamma-uranium phase, or some gamma-phase transformation product other than alpha or alpha-prime. Molybdenum, niobium, titanium, and zirconium are among those elements which form important binary systems. Metastable gamma alloys offer good performance in applications requiring high-temperature mechanical properties and corrosion resistance. The greatest improvement lies in high-temperature mechanical properties of these alloys.⁽⁷⁾

Aluminum and silicon form second phases (intermetallic compounds) with uranium, and will improve mechanical properties when added in small amounts. These small additions are known to produce grain refinement. If the compounds are present in larger amounts, or as coarse particles, they tend to produce brittleness in the alloy, and adversely affect fabricability.⁽⁸⁾

Uranium alloys show better corrosion resistance and strength than unalloyed uranium. Resistance to general corrosion increases with alloy content and appears to be inversely related to stress corrosion behavior. Stress corrosion resistance decreases as the alloy strength increases and occurs by two different modes, intergranular and transgranular, depending on the environment and the alloy. The effect of hydrogen on reducing ductility appears inversely proportional to alloy content. This response is similar to general corrosion behavior, i.e., resistance increases with alloy content.

PRODUCTION OF URANIUM ALLOY PARTS

In general, uranium and its alloys can be shaped into useful parts by casting, metalworking, and/or machining by practices similar to other construction materials. The main fabrication problem is chemical reactivity with the atmosphere, which requires special precautions in the casting, heating, and hot working of uranium alloys. On the other hand, machining uranium by conventional methods is relatively easy, provided proper tools and coolants are used to promote tool life and prevent burning. When dust and fine metal particles are produced during processing, adequate exhaust facilities are necessary to remove these fines from the air.

SAFETY AND LICENSE CONTROL

Radiation exposure is not a great problem to employees working in the presence of large quantities of these alloys. The main hazard in working with depleted uranium is the toxicity of fumes and oxides generated when working the metal hot, or when machining and grinding. The toxicity of such fines is largely related to the high density of uranium and the resulting dangers of heavy-metal poisoning.⁽⁷⁾ Operations producing such oxides and fumes should be vented through absolute filters. Residues, chips and oxides should not be casually discarded. Instructions on their handling and disposition are reviewed in this report and other reports.⁽¹⁾

The handling and possession of depleted uranium, except for certain specifically exempt items, is under Government license control when the quantity involved is over 15 pounds at any one time, or 150 pounds over the period of 1 year. Licensing procedures are contained in the Government publication:

Code of Federal Regulations
Title 10 - AEC, Chapter I - AEC
Part 40, Licensing of Source Materials*

In so-called "Agreement States", the licensing is arranged through the state nuclear materials control body.

The following sections describe the most common melting and casting techniques practiced by uranium-alloy producers, as well as investment-casting and permanent-mold casting techniques that appear useful in making near-net-shape parts of uranium alloys. Descriptions of metalworking, heat treatment, powder metallurgy, joining, and machining techniques for uranium alloys complete the production aspects of this report.

* Additional information can be obtained from the ERDA, Division of Licensing and Regulation, Nuclear Materials Section, Washington, D. C.

CASTING OF URANIUM INGOT

Uranium alloys have been melted and cast into round or slab ingots by most techniques. These include induction melting, vacuum-arc melting, vacuum-skull casting, electroslag remelting (ESR), and inductoslag melting.⁽²⁰⁾ The main precaution in melting is to isolate the molten metal from air either by vacuum or inert atmosphere. An added concern is to control the amount of impurities introduced by melting and to control segregation of impurities and alloying elements in the cast product.

Some of the general properties of uranium that influence casting parameters include its low latent heat of fusion and high density. A low latent heat of fusion allows rapid solidification, which reduces the likelihood of oxidation once the uranium is in the mold. Because of its high density, the metal easily pours and readily feeds the solidifying ingot. Unfortunately, the density of uranium can also promote gravity separation, where the lighter alloying element rises and segregates at the top of the ingot. The melting techniques applied to uranium solve such problems in various ways which are described in the following sections.

INDUCTION MELTING

Vacuum induction melting is a widely used technique for making uranium alloys. It requires relatively simple equipment, and considerable operating experience has been gained with it at various ERDA facilities, such as the Y-12 Plant, Oak Ridge, Tennessee, the National Lead Company of Ohio, and commercial facilities. Its major disadvantage is the potential for carbon contamination resulting from the graphite crucibles commonly used in this process.

The melting equipment consists of a cold-wall vacuum chamber that surrounds the crucible and induction coil lined with a high-temperature refractory such as Al_2O_3 . Figure 10 is a schematic of such a furnace used at the National Lead Company of Ohio.⁽²⁰⁾ The power supply is usually a motor-generator set employing a frequency low enough to provide electromagnetic stirring of the melt. Hot-wall units are also in current use.⁽³⁾

Vacuum systems are designed to evacuate the furnace to less than 100 microns and to keep the pressure buildup to typically less than 200 microns during melting. However, pressures as high as 850 microns and argon back filling to 15 torr have also been successfully employed with U-3/4 Ti. This is usually accomplished by use of positive displacement and blower-type pumping systems.⁽²⁰⁾

Crucible materials such as BeO, ThO_2 , MgO, CaO, ZrO_2 , and UO_2 have been successfully used to melt uranium.⁽²⁰⁾ However, graphite is the most commonly used for both crucibles and molds in the United States because of overall economics. To avoid uranium-carbon reactions and subsequent contamination of the uranium, various coatings are used to protect the graphite.

Crucible coatings of BeO, $BeSO_4$, ZrO_2-SiO_2 (Zirconite Wash A), $MgZrO_3$ (Magnesium-Zirconite Wash B) and Zircoa Set 5 (zirconium oxide) are applied as aqueous slurries by brush painting or air spraying. Adequate protection from carbon contamination can be obtained from this type of coating up to approximately 1300 C. Above this temperature, the coating begins to spall and become ineffective. However, washes similar to A and B have been used successfully on graphite crucibles for melting U-3/4 Ti at super-heat temperatures up to 1450 C without significant contamination.⁽³⁾ Critical considerations in the use of washes are both time and temperature.

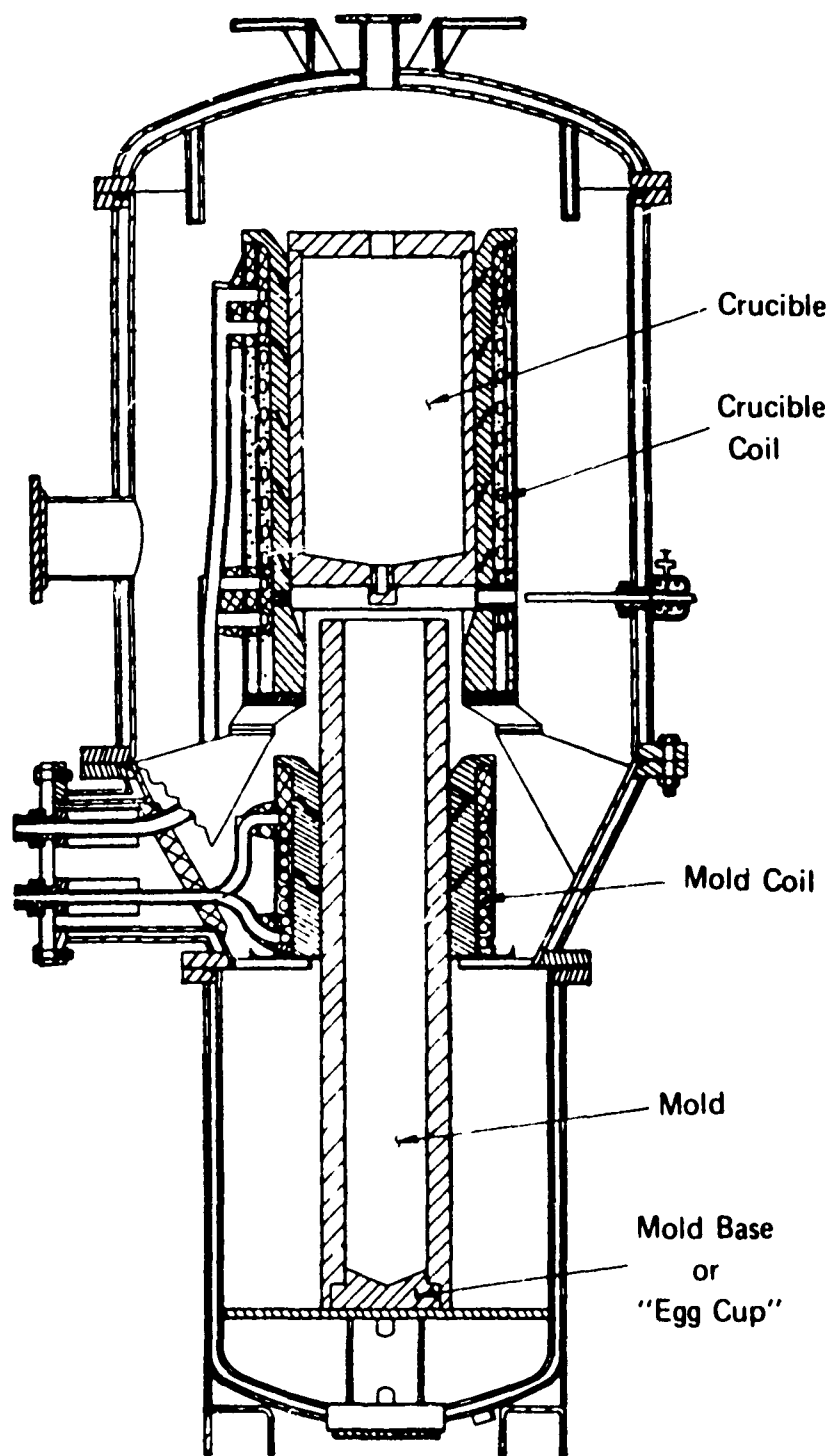


FIGURE 10. COLD-WALL STEEL SHELL FURNACE AT THE NATIONAL LEAD COMPANY OF OHIO⁽²⁰⁾

Flame spraying using an oxy-acetylene torch with zirconia powder is probably more effective than painting or air spraying of a slurry, but coating thickness is limited and variable. For high temperature applications, plasma spraying of magnesium oxide, zirconia and yttria-stabilized zirconia provides the most adherent coating and protection. Above 1400 C, however, most of these coatings deteriorate rapidly in contact with molten uranium. Recently, experimental work with multiple plasma-sprayed layers of niobium and zirconia, molybdenum and zirconia, or niobium, zirconia and yttria have proven to be very effective in reducing carbon contamination at temperatures up to 1550 C. These coatings, which are expensive and somewhat difficult to apply, require specialized equipment.⁽²⁰⁾

The coating requirement for the mold is considerably less stringent than for the crucible since only minimal molten metal contact occurs. A mold coating should withstand high-temperature shock and have suitable mold release characteristics. Uncoated graphite molds are sufficient for cold mold casting providing a dense grade of graphite is used. More commonly a mold is coated with a wash such as Zirconite Wash A ($\text{ZrO}_2\text{-SiO}_2$). The coating is applied with a brush from an aqueous slurry. A drying procedure usually follows the coating application to drive off residual moisture. If this treatment is not performed, a rough surface on the casting results from gas evolution.⁽²⁰⁾

Special alloying techniques have been devised to produce homogeneous uranium alloys. Direct additions of alloying ingredients can require long hold times for completely dissolving the elements into the uranium. Subsequent reaction of the ingredients with the graphite crucible if coatings deteriorate, may cause a significant change in the composition of the melt. This situation can be avoided by melting a prealloyed charge. Prealloying can be accomplished by arc melting either to the desired composition, or to a higher "master" alloy which can be diluted to the desired level. Since holding times can be reduced by using alloy additions with large surface areas, it has been found practical to make up dilute alloys of zirconium or titanium by placing readily available metal sponge of these materials at the bottom of the crucible. As melting occurs, the lighter elements tend to float up through the molten mass in the crucible and mix with the uranium. Induction and/or mechanical stirring and bottom pouring are common techniques to promote homogeneity in the cast ingot. Bottom pouring is recommended to minimize inclusions in uranium alloy ingots because most insoluble oxides, carbides, nitrides, etc., and intermetallics float during melting. Examples of induction-melting practices for uranium alloys presented by Cadden, Jessen, and Lewis are shown in Table 18.⁽²⁰⁾

ARC MELTING (VAR)

Consumable d-c arc melting is used to produce uranium alloys when low impurity material is desired because of the lack of contamination from crucibles. It also is of value as a means for producing the rich alloys with relatively low segregation.

In arc melting the uranium charge is welded, pressed, or machined into a long cylinder. The cylinder, when placed into a vacuum arc-melting furnace, is usually attached to the negative electrode of a d-c power supply. A water-cooled copper mold is attached to the positive side of the power supply, and when the electrode contacts the mold, an electrical arc occurs. This electric arc, which in itself is a complex phenomenon, melts and transfers molten metal from the electrode to the water-cooled mold where it solidifies rapidly.⁽²⁰⁾ This rapid cooling means that solidification occurs in a narrow range and reduces gross segregation in the ingot. However, enough segregation occurs in some of the higher alloys to make it advisable to double-arc melt. In these cases, the top and bottom of the ingot are usually removed to eliminate the impurities that had floated to the top of the molten zone and to remove copper contamination from the mold respectively.

TABLE 18. TYPICAL INDUCTION MELTING PRACTICE FOR URANIUM ALLOYS(20)

Uranium Alloy Weight Percent	Charge Material	Weight Kilo-grams	Crucible Coating	Mold Coating	Ingot Shape	Power Frequency Kilo-watts /Sec.	Melting Cycle	Mold Temperature (°C)	Typical Chemical Results	
									Top	Bottom
U-3/4 Ti	Derby Uranium, Titanium Sponge, and Recycled Uranium	360	Plasma-Sprayed ZrO ₂	Zirconite Mold Wash (A)	Slab 4"x20"x20"	175	1370°C-Cool to 1320°C-Hold 30 Minutes-Pour	1000°C Top Min. 700°C Bottom	0.785 w/o Ti; 30 ppm C	0.756 w/o Ti; 25 ppm C
U-0.65 Zr	Recycled Uranium Zirconium Sponge	15	MgZrO ₃ Brush Coated	MgZrO ₃ Wash	Slab 1"x5"x7"	45	1310°C-Hold 10 Minutes-Pour	-----	0.60 w/o Zr	0.58 w/o Zr
U-10 Mo	Derby Uranium and Molybdenum Powder	1055	Plasma-Sprayed Yttria-Stabilized ZrO ₂	MgZrO ₃ Wash	Slab 8"x20"x20"	175	1450°C-Hold 30 Minutes-Pour	360°C Top 225°C Bottom	10.59 w/o Mo; 88 ppm C	10.31 w/o Mo; 87 ppm C
U-6 Nb	Prealloyed By Arc-Melting	375	Plasma-Sprayed ZrO ₂	Zirconite Mold Wash (A)	5" Diameter 42" Long	175	1450°C-Hold 30 Minutes-Pour	1000°C Top Min. 700°C Bottom	5.94 w/o Nb; 79 ppm C	5.96 w/o Nb; 87 ppm C
U-8 Mo-1/2 Ti	Derby Uranium, Titanium Sponge, Molybdenum Powder	164	Plasma-Sprayed ZrO ₂	MgZrO ₃ Wash	7" Diameter 14" Long	60	1425°C-Hold 15 Min. Cool to 1350°C-Hold 15 Minutes-Pour	-----	7.96 w/o Mo; 0.85 w/o Ti; 31 ppm C	7.364 w/o Mo; 0.666 w/o Ti; 8 ppm C
U-3/4 Mo-3/4 Zr-3/4 Nb-1/2 Ti	Derby Uranium, Titanium, and Zirconium Sponge, Molybdenum Powder, Niobium Chips	360	Plasma-Sprayed ZrO ₂	Zirconite Mold Wash (A)	Slab 4"x20"x20"	175	1425°C-Hold 15 Minutes-Pour	-----	Mo 0.84 Nb 0.68 Zr 0.80 Ti 0.58	C 29 D _{PM}
U-5 Zr*	Co-reduction UF ₄ + Ca (4% excess) + Zr Fines (100% excess)	230	MgZrO ₃ Wash	MgZrO ₃ Wash	5" Diameter	200	1370-1425°C-Hold 1-1/2 Hours-Pour	-----	5.23 w/o Zr; 50 ppm C	4.72 w/o Zr; 50 ppm C
U-5 Mo* (Double Melt)	Co-reduced UF ₄ + Mo Powder + MoO ₃ (50% excess)	230	Zr Crucible for First Melt. Second Melt BeO Wash	MgZrO ₃ Wash	5" Diameter	200	1260°C-Long Hold-Pour/Second Melt 1370°C-1-1/2 Hour Hold-Pour	-----	Carbon less than 500 ppm	
U-(ppm Add)-Alloys*	Alloying materials Charged as Powders 1200 C, 300 Ni, and/or Chips 500 Fe, 150 Cr, and 250 Si	545	Not Coated	Not Coated	7" Diameter	200	1400°C-1 Hour Hold-Pour	-----	C-1120 ppm, Ni-330 ppm, Fe-530 ppm, Cr-160 ppm, Si-270 ppm	
U-0.075 Al*	Derby Uranium, Aluminum Pellets (Al in Mold)	---	Not Coated	Not Coated	13" Diameter	200	-----	-----	Reported as Excellent Ingot Homogeneity	

* National Lead of Ohio (NLO) Procedure

OTHER MELTING PROCESSES

Less common melting practices used with uranium are briefly described in the following:

Skull Casting

Vacuum skull melting is a variation of the cold mold vacuum arc-melting technique. The term "skull" signifies that a liquid pool of metal is contained in a solid skull of the same metal. A skull is maintained by control of the relative rates of power input to the liquid and heat loss through the skull. Specific features associated with skull melting furnaces are: (1) pouring capability -- by tilting or bottom discharge, (2) consumable or nonconsumable electrodes, and (3) ability to cast shapes. Skull-melting furnaces are inherently more complicated than ordinary vacuum arc furnaces, and are used only for special melting situations. Specific advantages of the skull-melt furnace are that it provides an excellent method for consolidating irregularly shaped scrap and a method for homogeneous alloy mixing under noncontaminating conditions.⁽²⁰⁾

Skull melting and casting is a reliable and efficient method for producing uranium alloy ingots. However, when considering the melting of alloys whose constituents have much higher melting points than uranium, it is advisable to use prealloyed electrodes. The most effective use of the skull-melting furnace is for consolidating uranium alloy scrap. The scrap, which can be placed directly into the crucible, melts as the electrode is consumed.⁽²⁰⁾

Electroslag Refining (ESR)

Electroslag refining is a secondary remelting and refining process for metals and alloys. It uses as its raw material an electrode of the material to be remelted which may be cast, wrought, or briquetted.

The ESR process is similar to the vacuum arc remelting process. The principal difference between the two processes is that the heat for electroslag melts is generated from the resistance of a current carrying slag rather than from an arc. For most metals and alloys, the slag provides a protective cover for the molten pool and eliminates the necessity for costly vacuum systems which are required for VAR. Again, reactive and refractory alloys must be ESR melted in a closed system similar to that used for VAR. A furnace pressure of approximately two-thirds atmosphere (10 inches of mercury) with a backfill of an inert gas has been found to be satisfactory for these melts.⁽²⁰⁾

Straight polarity, d-c ESR melting of a uranium-7.5 weight percent niobium-2.5 weight percent zirconium alloy has been shown to be an effective technique in reducing oxygen contamination. Initial experiments using 100 percent CaF_2 as the slag resulted in a slight increase in oxygen content and a dispersion of the metallic oxide into finer particulates. Additions of from 1 to 10 weight percent MgF_2 indicated slight reductions in oxygen but the surface conditions of the ingots were rough in comparison.

Blending up to 4.4 weight percent calcium metal with the CaF_2 slag reduced the oxygen level to that expected in virgin VAR melted material. Ingot surfaces again were quite rough and melting conditions were erratic.

The favorable solidification mode and refining capabilities make the ESR process attractive where product quality is at a premium. These melting techniques are used successfully to produce high-quality ingots of superalloys and specialty steels and should be applicable to uranium and uranium alloys. However, additional work appears to be needed in order to firmly establish the parameters for electrosag melting uranium and its alloys on a routine basis.⁽²⁰⁾

Inductoslag Melting

In this process the molten metal is induction melted in a water-cooled crucible and the molten metal kept separated from the crucible walls by a layer of slag. It has been used successfully at the Y-12 Plant to melt U-7.5 Nb-2.5 Zr.⁽²⁰⁾ With a slag mixture of 52 weight percent CaF_2 -48 weight percent MgF_2 , the oxygen level of a 38-inch ingot was found to be in the range of 19 to 48 ppm, which indicated that a reduction in oxygen levels had been achieved. This is a unique process for melting high-purity uranium alloys, but, because of the complexity of the melting equipment and of the slag-molten metal-container interface, the process will likely remain a specialized process to supplement other melting processes.

PRECISION CASTING

In the previous descriptions of uranium melting practices the final products are typically round or slab ingots. These ingots can be machined to the final configuration, or more commonly are machined all over and then processed into mill shapes by various combinations of rolling, extrusion, and forging. Because of this subsequent processing, the as-cast dimensions and surface finish of the ingot are not usually critical parameters. However, in some large-scale applications of depleted uranium such as penetrators it may be essential to cast parts to near net dimensions with sound surfaces in order to minimize processing costs.

Two precision casting processes recently used to produce uranium penetrators are investment casting and permanent mold casting. Each of these processes is described.

INVESTMENT CASTING OF DEPLETED URANIUM PENETRATORS

Investment casting is a precision casting process using an expendable ceramic mold. This ceramic mold is produced by coating a wax-like pattern and gating system with multiple layers of a refractory slurry that sets at room temperature. Before casting, the ceramic mold is heated and the wax-pattern material poured out leaving behind a mold cavity with the precise shape of the desired part, and the gating system to feed the molten metal. Typically, each ceramic mold has multiple cavities. A single mold may produce 10 to 1000 similar parts depending on the size of each part.

Each of the initial wax-patterns can be produced by injecting a molten wax or plastic material into a metal die cavity much like die casting. The pattern is thus readily reproducible, and, since the ceramic mold conforms closely to the pattern, the mold cavities are reproducible, as are the final castings. Additional details of the investment-casting process can be found in References 21, 22, and 23.

A program at NMI (Nuclear Metals Inc.) has produced penetrator shapes in depleted uranium using the investment-casting process.^(4,24) In this program, all melting was done in a vacuum-induction furnace of the external coil, quartz-tube type. Power was supplied by a 100 kw, 3000-cycle motor

generator. The 85- or 152-pound charge consisted of depleted uranium in several pieces and titanium sponge in chunks no larger than 1/2 inch in major dimension. The charge was located in a 9-inch-ID graphite crucible. This crucible was precoated with a calcium-stabilized zirconia wash and fitted with a similarly coated graphite stopper rod seated in a 3/4-inch-diameter pour hole in the bottom of the crucible.

The most successful mold facings were obtained with zirconia (ZrO_2)—zircon ($ZrSiO_4$) mixture with a 5 percent colloidal silica binder. Less than 95 percent zirconia in the facing was found to promote surface quality. Subsequent backing materials were not explicitly discussed, but were noted to be of high permeability to facilitate outgassing. Mold preheating to 925 C was necessary to eliminate surface porosity. Lower preheat temperatures were used, but the higher temperature produced better quality penetrators.

The furnace and the mold chamber, were first evacuated to less than 40 microns, and the charge then heated at the 30 to 35 kw setting. Power levels were adjusted to obtain the superheat conditions of up to 1400 C for 30 minutes. The melt was then allowed to cool to pouring temperature, either 1300 or 1200 C. Total furnace time before pouring was 72 ± 4 minutes after the initial charge heatup. The mold was removed from the preheat furnace and placed in the vacuum furnace two hours before heatup started.⁽⁴⁾

After the mold and castings were removed from the chamber, the mold was broken away with a hand tool. The castings were then cut free from the gating system with a power hacksaw.⁽⁴⁾ Figure 11 shows the cluster of castings obtained.

Nuclear Metals reported that bowing of the cast-penetrator blanks seemed to be a main problem area. Penetrators deviated from straight in the range of 0.002 to 0.060-inch TIR (total indicated runout) with an average of 0.025-inch TIR.* Solution heat treatment of the as-cast blanks produced an additional bow of 0.010-inch TIR.⁽²⁴⁾

It was suggested that more uniform cooling of blanks after casting and heat treatment would reduce bowing. Unless straighter parts are produced, a straightening operation becomes necessary to avoid large cleanup allowances and inefficiencies in finishing operations.⁽²⁴⁾

Generally excellent cast surfaces free of significant mold reaction were obtained using a 925 C mold preheat temperature, and mold facings 0.020-inch thick. However, surface inclusions (from spalled mold coating) and subsurface inclusions of mold material and dross particles were present in small amounts. Two-thirds of the castings produced had some minor gas porosity; however, the causes contributing to this situation remain undetermined.⁽²⁴⁾

It appears that this process has promise as a means for producing low-cost penetrators, but the economics of the process have not been rigorously established.

PERMANENT MOLD CASTING

The permanent mold process⁽²³⁾ has been used to cast penetrators of the uranium alloys, U-3/4 Ti and U-3/4 Quad.⁽⁵⁾ Figure 12 illustrates the mold used to cast eleven uranium-alloy penetrators with each pour. The downsprue and main runner at the bottom of the mold have rectangular

* The wax patterns, subsequently made more precise by the use of one-piece die, had measured bows of only 0.007-inch TIR maximum in some cases.



FIGURE 11. CASTING MADE IN THREE-TIER MOLD⁽²⁴⁾



FIGURE 12. PERMANENT MOLD DESIGN FOR CASTING DEPLETED URANIUM PENETRATORS⁽⁵⁾

cross sections to minimize turbulence during pouring. It also shows a continuous riser across the top. The mold was made of Meehanite with the penetrator cavities, runner, and risers machined into removable inserts so that these details could be modified independently.⁽⁵⁾

A plasma-sprayed calcia-stabilized zirconia coating was found to be the most suitable mold coating to prevent reaction of the molten alloys with the Meehanite mold. The coating procedure involved removing of oil and grease from the mold surface, followed by light sandblasting to roughen the surfaces for increased adherence of the coating. Next, a 0.002-inch bond coat of nichrome was plasma sprayed onto the mold. Nichrome was used because it has a coefficient of thermal expansion intermediate between that of iron and zirconia. Consequently, this bond coat increased adherence and reduced spalling. Finally, a 0.005-inch layer of calcia-stabilized zirconia was plasma sprayed onto the mold.⁽⁵⁾

The mold temperature for casting U-0.75 Ti was set around 600 F. The molds were first preheated in air to near their operating temperature, then placed below the crucible in the vacuum melting furnace. Final mold temperature was achieved by the use of resistance heaters placed on top of the mold. The measured temperature gradient was 620 F to 560 F, top to bottom.⁽⁵⁾

The molten metal was poured into permanent molds at approximately 2450 F, as measured by an optical pyrometer. However, this temperature was difficult to control because of the small quantity (27 lb) of U-0.75 Ti in the crucible. Also, the casting results were very sensitive to metal temperature. Overheating the melt by 50 F produced pipe in the castings. Underheating the melt by 50 F produced some misruns.⁽⁵⁾

After the castings were poured and allowed to solidify, the vacuum chamber was opened to the air and the castings removed from the mold.

Although procedures were developed to eliminate radiographically observed defects in the castings, the machined surfaces revealed that many castings had very small random pores about 0.010 to 0.020-inch diameter. Most of the subsurface porosity was located in the outer 0.010 inch of the cast surface and usually removable by machining. The penetrators had been cast with an envelope thickness of 0.050 inch to allow for runout and to clean up surface imperfections. The runout resulting from heat treatment was in the range of 0.020 to 0.030 inch.⁽⁵⁾

Additional work would be required to optimize the mold designs and mold materials and to obtain precise cost figures for the operations but the feasibility of the permanent mold casting of uranium alloys has been demonstrated.

MECHANICAL WORKING

Uranium and its alloys have been successfully worked by all common metalworking processes. However, extrusion, rolling, forging, and swaging have been the most common. Typically, the starting material is machined ingot to provide improved billet surface quality which is usually reflected in the product quality. However, machining may not be necessary to achieve good surface quality if appropriate melting practices are used to promote good ingot surface quality.⁽³⁾ Primary working is usually achieved by extrusion or rolling^(2,25) to produce typical mill products such as rod, bar, tube, plate, sheet, etc. The major problems are oxidation, possible ignition, and poor workability associated with the β -phase either by overheating during alpha working or chilling from the gamma range. To avoid these problems, salt bath heating and molten ceramic coatings are employed with bare billets, copper cladding is used with air heating, and precise control of temperature and deformation rate are used to avoid β -phase associated problems.

Secondary working has been performed by a variety of processes,^(2,3,25) but usually in relatively small production lots. Present production forging has been performed on a header at production rates of 1200 pieces per hour and by swaging at 60 pieces per hour.⁽³⁾ The practices employed in these latter examples are similar to practices used for more common alloys.

The following will briefly review the state of the art and recent developments in the mechanical working of uranium alloys.

DEFORMATION CHARACTERISTICS OF URANIUM

Deformation of uranium up to 450 C (alpha phase) takes place mainly by twinning with work hardening occurring. Within this temperature range, a preferred orientation (010) develops in the material along the major axis of working. As the working temperature is increased above 450 C, a dual texture develops involving both (010) and (110) planes in the direction of working, and as the working temperature increases toward 600 C, the (110) plane becomes dominant. Uranium may be hot worked in this range since the metal gets progressively weaker and more ductile as the temperature is raised.^(7,8)

In the beta phase, 660-770 C, the forces required to hot work the metal are two to three times as great as at 650 C, and the ductility is substantially less. In this range, the worked uranium deforms by a slip mechanism. In the γ -phase, above 770 C, the body-centered cubic structure is usually too weak to retain its shape properly in forming operations, unless supported. However, extrusion may be carried out conveniently and with relatively little pressure. The variation in the hardness of uranium is shown as a function of temperature in Figure 13.^(7,8)

The more dilute alloys can be fabricated in both the alpha and gamma temperature ranges, but alpha processing is usually preferred. Gamma-phase processing is usually restricted to the higher alloys because of their greater high-temperature strengths. The primary difficulty encountered in the high-temperature gamma range is the heavy oxide formation and distortion.⁽²⁵⁾

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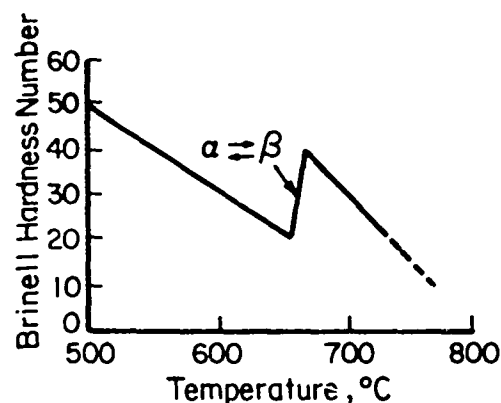


FIGURE 13. VARIATION IN HARDNESS OF URANIUM WITH TEMPERATURE

METALWORKING TECHNIQUES

Preheating for Working

Uranium reacts increasingly with air as the temperature rises but many working operations can be carried out without protection from oxidation. This applies to operations such as rolling and die forging which may be carried out rapidly in the high alpha range during which the die or roll pressure compacts the initial porous oxide film into a dense protective layer.

Protection during preheating is usually needed, but will depend on the heating time and temperature needed. The molten salt bath is the most common method with a variety of compositions based on chlorides and carbonates, such as eutectic lithium and barium carbonates, lithium and potassium carbonates, and chlorides or chloride/carbonate mixtures. Time in salt baths should be minimized to avoid surface degradation and hydrogen pickup, which will reduce ductility. During hot working, the salt stays molten, adheres to the surface and protects it from the air. Copper cladding of extrusion billets is employed with a variety of heating methods, including air furnaces, to enhance lubrication and eliminate contamination of equipment with uranium.^(7,25) Lead and lead-tin baths are also commonly used for uranium alloys, but adherence and/or reaction can occur on clean alloy surfaces. Induction heating has recently been employed for production forging and swaging of penetrators.⁽³⁾

Rolling

Rolling of uranium and its alloys is commonly performed with salt bath heating in the alpha range.^(2,7,25) Typical products have been rod, plate and sheet. The largest facility dedicated to the rolling of uranium alloys was constructed for the AEC in the early 1950's for preparation of feed material for reactor sites. This site is at Fernald, Ohio and operated by the National Lead Company. This equipment is based on high-alpha-temperature working⁽²⁾ and consists of a two-high reversing mill for ingot breakdown, a reheat salt bath, and a continuous finishing mill of six stands to the final reduction. Finishing speeds of up to 400 ft/min are possible depending on the final reduction. Typical practice involves rolling of cropped ingot, usually 8 inches in diameter, to nominally 2½-inch-diameter rod. After the finishing sequence, the rods are cut to length with a

flying shear and transferred to a walking-beam cooling bed or to a beta heat-treatment furnace. The primary purpose of the beta treatment is to minimize anisotropy. After cooling, the rod is Medart straightened.

A significant development effort and subsequent rolling and finishing experience were obtained as a result of the Fernald facility. This work is comprehensively reviewed in Reference 2.

Extrusion

Extrusion is a common primary metalworking method to produce rod and tube.^(2,7,25,28) Although most production has been performed on cast-and-machined billets,^(2,10) recent results⁽³⁾ with U-3/4 Ti indicate no effect of billet machining on rod quality or yield from billet. However, bottom pouring and proper mold preparation procedures were developed prior to this finding.

In general, there currently appears to be a preference for high alpha extrusion with careful control of preheat temperature and ram speed to avoid temperature excursions into the beta range. Gamma extrusion is employed to improve extrudability, particularly when press capacity is a problem,⁽¹⁰⁾ at the expense of straightness and handling on the runout table.⁽³⁾

Three basic extrusion practices are used:

- (1) Bare extrusion of billets heated in a molten salt bath^(3,10,26)
- (2) Extrusion of copper clad^(3,22) billets heated in air
- (3) Extrusion of glass-coated billets usually heated in air.^(25,28)

The actual selection appears to be economic because the quality and yield appear to be independent of the extrusion practice. Salt-bath extrusion of bare, machined and as-cast ingots with the liner and die lubricated with Fiske 604D have provided rod yields of 90 to 94 percent with dimensional control within ± 0.005 inch. Temperature and ram-speed control and periodic die conditioning were required to achieve this quality in nominally 100 foot extrusions of 5/8-inch-diameter rod. Copper cladding is used primarily to avoid machine contamination with uranium, but avoids the galling problems with bare billets. However, cladding can only be successfully used in the range of extrusion conditions where the cladding and the uranium alloy have similar strength; otherwise, the specific strength differences will produce "can rupture" and/or irregular rod dimensions.^(3,27) Glass coatings have the capability, if required, to avoid the problems with both bare and clad billets. It was found⁽³⁾ that Cu-clad billets of U-3/4 Ti could be successfully extruded in the beta range, but bare billets of virtually the same material fractured during beta range (approximately 1225 to 1425 F) extrusion.

Recent extrusion results have shown that melting practice and the original billet location in the ingot were factors causing yield variations between 45 to 94 percent.⁽³⁾ In general, the lower superheat times and temperatures, lower pour temperatures, and ambient mold temperatures provided the highest and most consistent yields of extruded U-3/4 Ti rod.

Forging and Swaging

The forging and swaging of uranium alloys are comprehensively reviewed in References 2 and 25. Forging is usually performed in the high alpha range and may be performed bare if precautions are taken during preheating. Press and hammer forging of uranium alloys have been performed in the

gamma range,⁽²⁵⁾ but problems can be encountered due to rapid oxidation and tooling-workpiece interaction because of the low-melting (740 C) U-Fe eutectic.⁽²⁵⁾ The metastable alloys, U-5% to 15% Mo, have been successfully hammer forged at 980 C. To minimize the problems of oxidation, it is not uncommon to oil or water-quench after forging.⁽⁷⁾

Forging has been used for breakdown of the cast structure in both ingot and derby.⁽²⁾ However, extrusion and rolling have become the most common primary working methods. Ingot forging of uranium alloys is similar to the forging of ingot of other alloys.⁽⁸⁾ Care must be exercised to avoid end burst and to achieve the refinement of the cast structure. The most recent developments in forging uranium alloys have dealt with high-volume production applications for penetrators.^(3,5)

The production feasibility for manufacturing depleted uranium-alloy penetrators by extrusion-forging was demonstrated for the U-3/4 Ti and U-3/4 Quad alloys using the die-punch assembly shown in Figure 14. The starting material for this forging was nominally 3/4-inch-diameter extruded rod which was forged directly, or after preforming with a partial nose (nominally 25 percent of full form) in the die cavity in Figure 15. Preforming was performed by either room-temperature swaging, warm forging, or machining. The U-0.75 Ti alloy was readily cold-swaged in either the as-extruded or the solution heat treated and overaged conditions. Although both alloys in the solution treated condition could be cold-swaged, the room-temperature formability was not as good as either of the two other metallurgical conditions.

It was not possible to swage the U-0.75 Quad to the desired preform configuration, irrespective of metallurgical condition. However, when the material was overaged, the desired preform configuration could be readily warm forged in the temperature range of 560 to 600 C. The maximum punch pressure required for the preforming operation was only 275.8 MPa (40,000 psi).

Forging was performed with the die heated to 260 C (500 F) at a ram speed of 34 mm per second (80 inches per minute). Fiske-BMI No. 4 Hot Die Lube* was applied to the die by swabbing a few seconds before each forming trial. The uranium alloy preforms were heated to the desired temperature in a molten lead bath for 2.5 minutes. After forging, the penetrators were ejected and then quenched vertically into a water bath. The peak punch pressures required to form the penetrators are given in Table 19.

The low punch pressures recorded for the U-Ti alloy indicated that it might be possible to form the penetrator configuration with only one forging operation using an unnosed preform. Although square-ended preforms are not generally recommended because of potentially increased die wear, unnosed U-0.85 Ti preforms were successfully forged to the desired shape at a temperature of 600 C (112 F) and a peak punch pressure of 765 MPa (111,000 psi).⁽⁵⁾ Typical hardness increases as a result of forging were in the range of 4 to 10 Rc points and inversely proportional to the initial hardness.

Swaging of uranium has been a convenient way of producing small diameter rod. It is best carried out in the alpha range around 560 C, and 10-20 percent reductions per pass are usual. In cold-swaging uranium, it may be necessary to anneal after 30 to 40 percent reduction.⁽⁷⁾

U-3/4 Ti alloy penetrators are being routinely swaged at NMI and warm forged at Omark Industries.⁽³⁾ In both operations essentially α -extruded rod is used as the starting stock after straightening. Shear-cut, double-lengths blanks are used for swaging preforms and centerless ground and chamfered

* Fiske Bros. Refining Company, Toledo, Ohio.

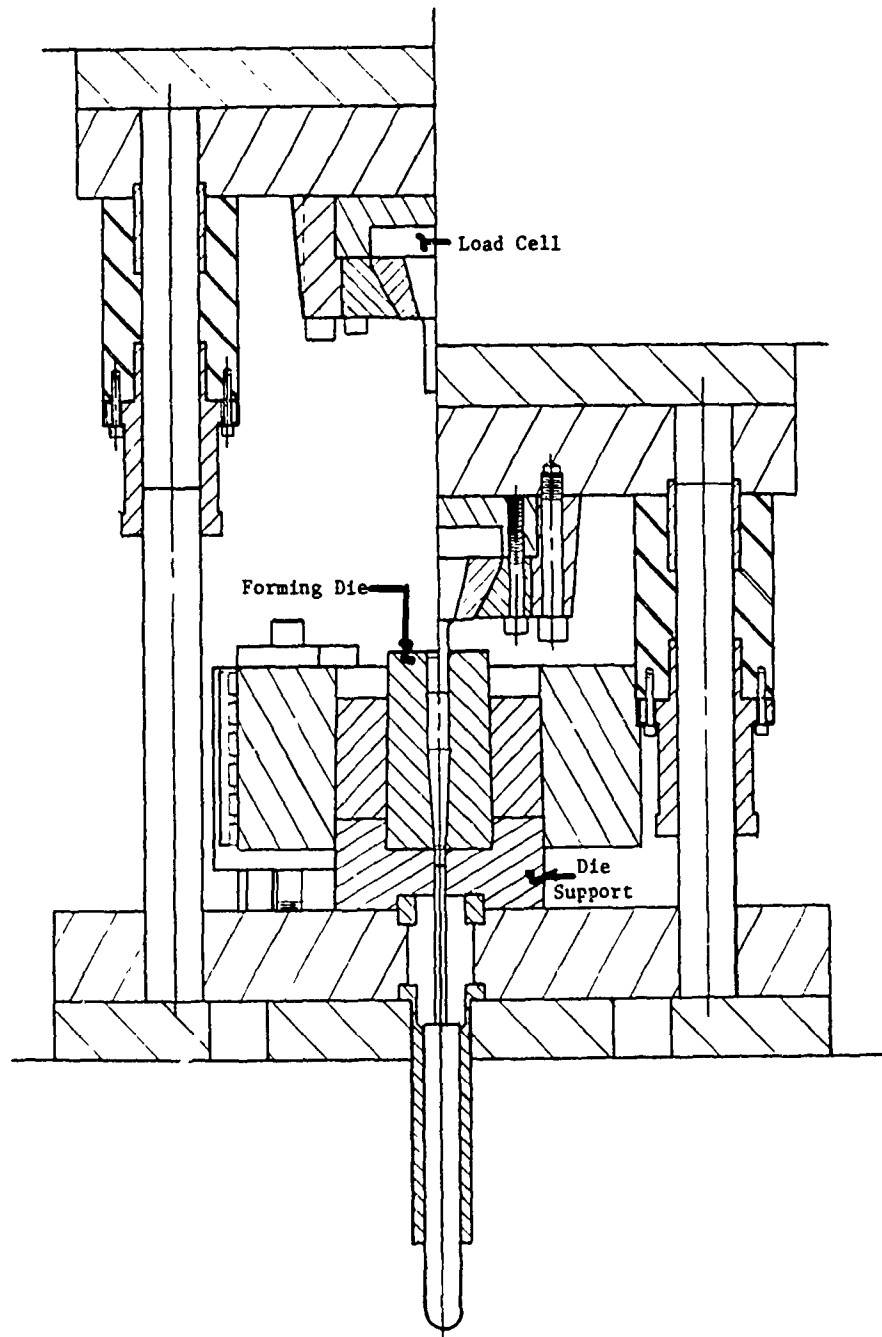


FIGURE 14. TOOLING FOR EXTRUSION-FORGING⁽⁵⁾

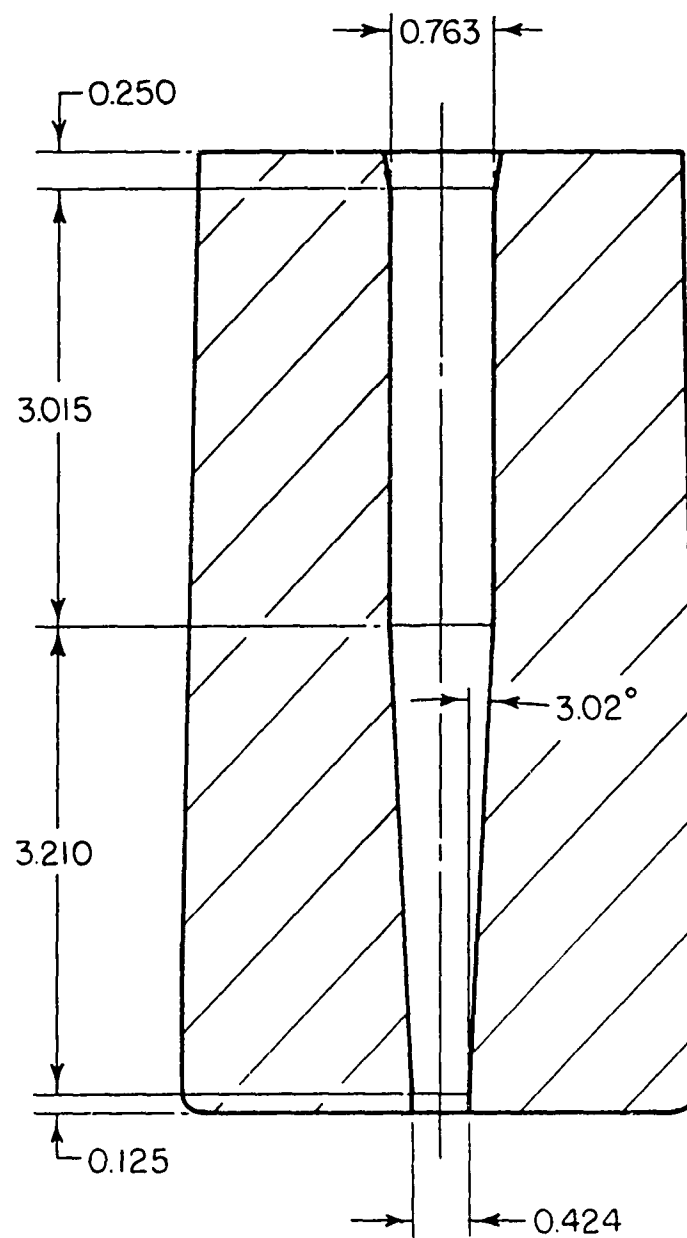


FIGURE 15. DIMENSIONS OF DIE USED FOR EXTRUSION FORGING TRIALS

TABLE 19. PEAK PUNCH PRESSURES REQUIRED TO FORM PENETRATORS

Alloy	Metallurgical Condition	Forming Temperature, C	Preform Type	Peak Punch Pressure, MPa (psi)	Average Forged Hardness, R _c
U-0.75 Ti	As-extruded + 6 hr at 600 C	600	Nosed	241 (35,000)	29
U-0.85 Ti	Solution Heat Treated + 6 hr at 600 C	600	Nosed	386 (56,000)	37
U-0.85 Ti	Solution Heat Treated + 6 hr at 600 C	600	Unnosed	765 (111,000)	—
U-0.75 Quad	As-extruded + 6 hr at 600 C	600	Nosed	972 (141,000)	41
U-0.75 Quad	As-extruded + 6 hr at 600 C	650	Nosed	814 (118,000)	40
U-0.75 Quad	Solution Heat Treated + 6 hr at 600 C	650	Nosed	696 (101,000)	47
U-0.75 Quad	Solution Heat Treated + 6 hr at 600 C	650	Unnosed	>1380(>200,000) ^(a)	—

(a) Desired shape could not be formed from unnosed U-0.75 Quad preforms.

prelubricated slugs are used as forging preforms. Induction heating in air is used for both operations with a total heating time of 20 to 40 seconds. In the swaging operation, one end of the slug is heated to 950 F and swaged. This operation is later repeated on the other end. The swaging is done at the rate of 1 piece per minute. In the warm forging operation, precisely sized blanks are gradient heated to a maximum temperature of 1050 F and header forged at 1200 pieces/hour.

The dimensional precision of products from both processes is excellent, but subsequent solution treatment produces significant distortion which appears to be a function of the solution-treatment technique. To avert this distortion and facilitate finishing, both processes have employed a cold re-strike for straightening.⁽³⁾

HEAT TREATMENT

The properties of uranium and uranium alloys are changed dramatically by heat treatment. The changes in pure uranium result mainly from allotropic transformations in the crystal structure. However, uranium alloys not only have the potential for allotropic changes, but also many of these alloys are subject to aging reactions. Therefore, heat treatments of the unalloyed uranium will be described first, followed by a discussion of heat-treatment parameters for uranium alloys.

Uranium

Uranium transforms from alpha to beta at 668 C, and from beta to alpha at 776 C. Heating to the gamma range can result in a very coarse, stress-free alpha grain size if the material is slow cooled. Water-quenching can minimize the alpha grain size, but can introduce some residual stresses.

Heating into the beta range is used to reduce the alpha grain size. This particular heat treatment is used to minimize preferred orientation normally present in alpha-worked uranium structures. Time and temperature within the beta range are not critical except to allow time for the part to uniformly heat and transform.

Heating uranium in the high alpha range, say 600 C, converts the heterogeneous as-quenched beta structure to a fine-grained equi-axed structure. This same thermal treatment also relieves the residual stresses that result from either alpha working or quenching from the gamma region.

Heat Treating Metastable High Alloys

The normal heat treatment for the high alloys, i.e., alloying content greater than 4.0 niobium, molybdenum, or equivalent, begins with a solutionizing treatment in the gamma phase region (above approximately 800 C), holding for the desired time (approximately one hour), and then either (1) rapidly cooling the alloy to room temperature and subsequently age hardening at some low temperature, or (2) quenching directly to the aging temperature and holding, depending on the production schedule and desired properties.⁽²⁵⁾

Solution Heat Treatment. The time at solutionizing temperature is not critical unless the final grain size is important. Oxidation of the surface and severe degradation will occur on thin, delicate parts unless vacuum or atmospheres are used. If such facilities are not available, it is advisable to reduce the time at which the part is at temperature to about 5-10 minutes.⁽²⁰⁾

Quench cracking is common in the U-2.3 Nb alloy and others with small amounts of alloying element. Cracking has also occurred in large diameter billets of U-6 Nb which were water quenched from 800 C. The U-10 Mo alloy is very sluggish in transforming from the gamma phase and usually does not require quenching. The crystal structures obtained by solution quenching are slightly different for each alloy, but they can be transformed into the equilibrium phases by reheating to temperatures up to about 640 C. A wide variation in mechanical properties accompanies this decomposition.⁽²⁵⁾

Age Hardening. Some general points to consider in the selection of aging treatments for U-Nb alloys are as follows. The solution quenched metastable structure is the most corrosion resistant; the overaged structure the least. The solution quenched structure is usually the softest and most ductile. The elastic modulus is lowest in the solution quenched condition and it increases steadily with increased aging. The U-7.5 Nb-2.5 Zr alloy has the lowest modulus of the alloys in the quenched state, about 7×10^6 psi. The yield strength increases and ductility decreases with increasing aging temperature up to about 350-400 C. Overaging then causes a decrease in yield strength and, above 500 C, an increase in ductility.

Aging in the normal range up to 300 C can be carried out in recirculating furnaces or ovens using air or inert atmosphere. Long-time aging treatments for the U-2.3 Nb alloy should be performed in vacuum if possible because of the greater oxidation rate compared to the other alloys. Overaging of all alloys should be performed under vacuum or well-controlled inert atmosphere. Because of rapid changes in properties during aging, precise furnace or oven controls (± 2 to 5 C) are required for quality control of the final mechanical properties. It is usually advisable to choose as low an aging temperature and as long a time as practical to minimize the variability in properties.⁽²⁵⁾

Heat Treating Dilute Low Alloys

The heat treatment of the dilute uranium alloys having small additions of titanium and molybdenum, always consists of a solutionizing treatment in the gamma-phase temperature range (approximately 800 to 850 C), followed by quenching to room temperature, and then by artificial aging.

A second treatment involves direct quenching from the solutionizing temperature into baths of molten metal or salt at the appropriate temperature to develop the desired hardness. Figure 16 is a summary of the results of work done at Los Alamos on heat treating various U-Ti compositions using various aging temperatures and aging media. This figure illustrates a very low sensitivity of hardness to variations in titanium content. Figure 17 is a summary of hardness results versus various heat treatments for a U-2 Mo alloy. The materials which were produced by these heat treatments generally possess very high ultimate tensile and yield strengths with very low elongation and poor fracture toughness. For this reason the value of these heat treatments for producing useful structural shapes is subject to question.⁽²⁵⁾

Considerable effort has been expended to develop heat treatments that will yield materials possessing high tensile and yield strengths with reasonable ductility. Heat treatments have been developed for a U-0.75 Ti alloy that consistently produce material possessing the following minimum properties:

- 200 kpsi ultimate tensile strength
- 200 kpsi yield strength
- 10 percent elongation.

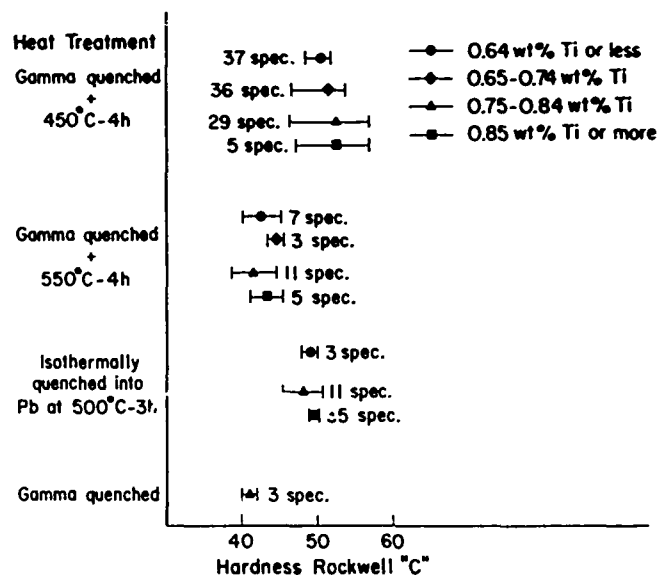


FIGURE 16. HARDNESS VERSUS HEAT-TREATING CONDITION FOR VARIOUS U-TI ALLOYS AGED IN DIFFERENT MEDIA AND AT DIFFERENT TEMPERATURES⁽²⁵⁾

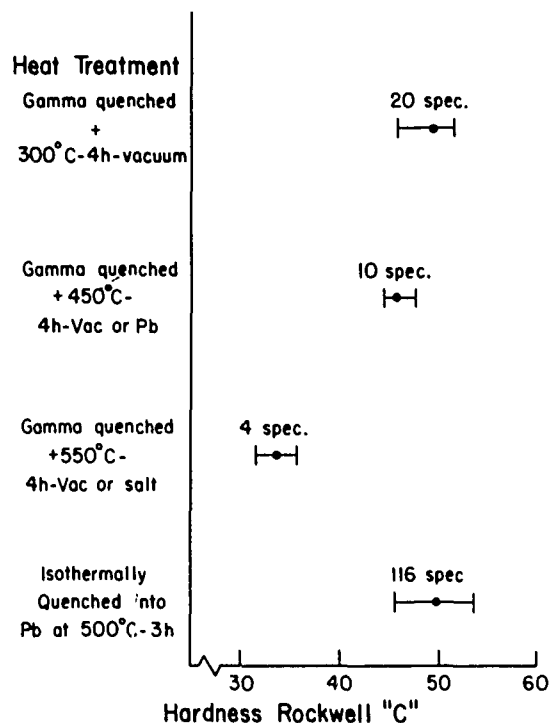


FIGURE 17. HARDNESS VERSUS HEAT-TREATING CONDITIONS FOR A U-2 MO ALLOY HEAT-TREATED IN VARIOUS MEDIA AND TEMPERATURES⁽²⁵⁾

The heat treatments used to produce these properties involve heat treating the material into the gamma phase (approximately 800 C), quenching to room temperature, and finally artificially aging at 375 or 400 C for 6 or 4 hours, respectively. Extreme care must be taken in these treatments to insure that the material does not pick up hydrogen during the heating cycle or there will be a dramatic loss in ductility. Investigators at Y-12 have shown that hydrogen contents of the heat-treated material must be held to less than 1 ppm if good ductility is to be realized in the heat-treated part. Hydrogen contents less than 1 ppm can be easily achieved in U-0.75 Ti alloys using the following heat-treating procedures:

- (1) Extrude starting stock in the gamma-phase field
- (2) Vacuum outgas the extruded bar at 875 C for 2½ hours at 10^{-5} Torr. Furnace cool to room temperature
- (3) Gamma heat treat at 850 C for 1 hour in flowing argon. Quench into H₂O
- (4) Age at the specified aging treatment in vacuum or molten lead for a time dependent on properties required.

A very serious problem has been associated with the development of centerline quench defects in gamma quenched U-Ti alloys. These defects have the appearance of voids in the material. Studies of this problem showed that the voids were produced by the quenching operation from the gamma heat treatment. The general conclusion regarding the development of the centerline defect in gamma quenched dilute alloys was related to the very low thermal conductivity of uranium and the attendant volume changes which occur when the alloy transforms from the high-temperature gamma phase to the room-temperature alpha phase.⁽²⁵⁾

Javorsky at Los Alamos studied the quench-rate sensitivity of U-low titanium alloy by quenching specimens of U-Ti alloys into various quenching media and relating their cooling rates as a function of quenching media. Figure 18 shows a plot of cooling rate for five different quenching media. After quenching in the various media, samples were artificially aged at 350 C for various times. Figure 19 shows that for all quenching media, except the argon gas quench, the response to aging is identical with regard to hardness for all of the different cooling rates. Additionally, the quenching rates in the range of 38 to 40 C sec⁻¹ and slower were completely adequate to eliminate centerline defect formation in the 0.875-inch-diameter stock. Subsequent mechanical testing also showed that the mechanical properties developed in the oil quenched plus aged materials were identical to those obtained from H₂O quenched plus aged U-Ti alloys.⁽²⁵⁾

POWDER METALLURGY

Powder-metallurgy uranium is in an early stage of development.⁽²⁹⁾ Uranium-alloy powders have been made by direct-reduction⁽³⁰⁾, gas-atomization⁽³¹⁾, plasma-spray⁽³²⁾, and by the rotating-electrode method⁽³³⁾. Uranium-alloy powders have been consolidated by prepressing and sintering, hot-pressing, hot isostatic pressing, and hot-working.⁽²⁹⁾ Once consolidated powder-metallurgy uranium can be further worked by conventional metalworking operations, but few data are available on material processed in this manner.⁽²⁹⁾

The major problem in the powder-metallurgy approach is that the uranium powder is readily embrittled by interstitial impurities and oxidizes readily to levels beyond 100 ppm. Further, the

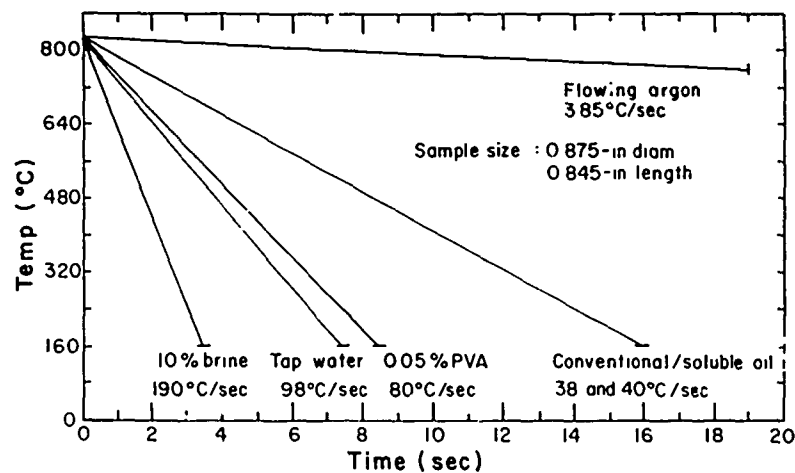


FIGURE 18. COOLING RATE FOR VARIOUS QUENCHING MEDIA ON DILUTE U-TI ALLOYS⁽²⁵⁾

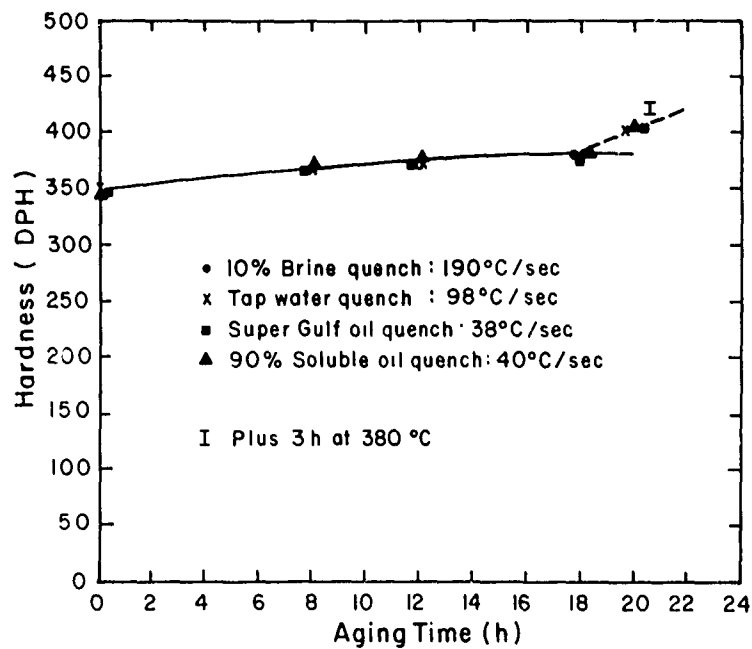


FIGURE 19. HARDNESS VERSUS AGING TIME FOR A DILUTE U-TI ALLOY AS A FUNCTION OF QUENCHING MEDIA⁽²⁵⁾

particle sizes must be kept above 10 microns to avoid pyrophoricity in the powder. For these reasons, it would appear that applications for uranium powder metallurgy will be confined to very special applications and alloys.

JOINING

Uranium alloys have been welded with a high degree of success. Most welding processes have been applied to uranium alloys, but electron beam and gas tungsten-arc welding are the most common. Probably more uranium alloys are welded by the electron-beam process than by any of the others, both by virtue of the vacuum environment and by the great amount of control which the operator has over the electron beam as a heat source. Furthermore, the electron beam is a very intense source of heat which can be used with high travel speeds to obtain very deep narrow welds with correspondingly narrow adjacent heat-affected regions.⁽³⁴⁾

Commonly, welds in most uranium alloys are autogenous, i.e., no filler material is added. Wire-feed mechanisms are developed to add filler material in electron-beam equipment, but obtaining a good quality uranium alloy filler wire remains a problem.⁽³⁴⁾ Existing wire typically has surface oxide trapped in folds at the wire surface, and the wire is brittle, and erratic feeding and porosity result from using it. However, the advantages of wire feeding are attractive enough that with increasing demand the wire-quality problems should be solvable.⁽³⁴⁾

The gas tungsten-arc process was the primary joining method for uranium alloys until the advent of the electron-beam process. Almost all of the early work was done by GTAW, and much of it has been repeated with EBW. A helium-filled dry box is commonly used rather than relying on shielding from the torch alone, although argon should be flowing in the torch to help initiate the arc. Also, gas-shielding methods, involving trailing shields and backup gas similar to those used to weld titanium, have been used successfully for welding uranium alloys.⁽³⁴⁾

It is especially important with uranium alloys to remove the oxide prior to welding if sound joints are to be obtained. Uranium oxide has a much higher melting point than the base metal and is relatively insoluble in the weld pool. As an inclusion it weakens the joint in proportion to its cross-sectional area relative to the weld cross section. Heavy oxide also interferes with the melting process, particularly in the arc of the GTAW process. Oxide should be removed within 24 hours of the time of welding. Methods used for removing oxide include: (1) wire brushing, (2) 1:1 nitric acid etch, and (3) electropolishing.⁽³⁴⁾

Details of technique and welding parameters must be changed for various uranium alloy compositions. However, even the more difficult-to-weld alloys (for example, some which contain molybdenum, niobium, titanium, or zirconium) can often be welded easily by careful selection of welding process and parameters. Details of welding parameters for various alloys are presented by Turner and Johnson.⁽³⁴⁾

MACHINING AND GRINDING URANIUM ALLOYS

The machining behavior of depleted uranium is essentially the same as that for enriched or natural uranium. These metals are considered differently only in terms of the types of radiological hazard with which they are associated. Depleted uranium contains considerably less of the active radio-isotopes, but nevertheless, care should be exercised in machining it.⁽³⁵⁾

Uranium exhibits certain behaviors that tend to make it more difficult to machine than conventional metals. Its high density requires extra cutting power and rigidity of setup. The metal is also highly susceptible to work hardening, and therefore, requires the same techniques as do other high work hardening metals like nickel and cobalt alloys. A high coefficient of friction, present during chip forming, causes high tool-chip temperatures, and the metal is slow in dissipating this heat.⁽³⁶⁾

Microstructure affects the machinability of metals, and uranium is no exception. For example, alpha uranium machines better if heated into the beta range and then quenched.

Another major factor in the machining of uranium alloys is the breakdown of cutting edges due to the presence of hard intermetallic compounds. For example, hard, abrasive NbC and Nb₂C particles present in a soft U-6Nb matrix dulls a tool edge about as effectively as diamond dust in a resin-bonded grinding wheel. As little as 150 ppm of carbon in the binary alloys of U-Nb can make these alloys very difficult to machine to close tolerances. The resulting dull tool imparts cold work into the part which can cause small dimensional changes with only slight temperature changes.⁽³⁷⁾

Probably the most critical property of depleted uranium is its pyrophoricity. Failure to provide adequate protection against this characteristic can lead to serious consequences. Fortunately, there are ways to control it. To prevent the occurrence of chip fires, copious quantities of a water-base coolant are used, and the cutting speed is adjusted to a rate under that which would cause the fire.

Uranium can be machined by standard shop practices, provided certain precautions are taken to minimize work hardening and high cutting temperatures.⁽³⁶⁾ The basic requirements include rugged, heavy-duty machine tools in good condition; vibration-free, rigid setups; high-quality cutting tools of special compositions; and heavy cuts using suitable cutting speeds and cutting fluids.⁽³⁸⁾ Since humid conditions accelerate the corrosion of uranium parts, all finished parts should be dried and coated with a light coat of thin oil and wrapped in plastic. Paper should not be used because it is hygroscopic.

A lack of knowledge on the machining of uranium alloys can be one of the major causes for rejected parts; hence, the skill and know-how used when these metals are machined cannot be overstated. The information given in this report should help to provide the guidance needed. Note, however, that too many factors enter into each machining operation to give unalterable sets of conditions. Nevertheless, the information given herein represents the parameters which have given the most success in machining depleted uranium.

SAFETY REQUIREMENTS

Experience at the Union Carbide's Nuclear Facility at Oak Ridge has shown that depleted uranium can be processed safely through careful handling, and by following personal and plant safety rules.^(35,36,37) These aspects are discussed as follows.

Handling Depleted Uranium Parts

Persons handling raw castings prior to machining or grinding should wear gloves, preferably rubber, to prevent being contaminated with residual oxides which may contain radiologically active daughter products. Outer clothing such as coveralls and safety shoes should be worn by all personnel doing machining, product inspection, and maintenance.

Personal Safety

Those working with depleted uranium should follow normal personal hygiene practices such as washing hands thoroughly before eating, and not laying cigarettes down on work benches. Personnel should also do their part to avoid fumes of metal-cutting operations, or burning chips even though ventilation is provided.

Much has been written about the proper health practices in handling depleted uranium. Available references provide detailed information on this phase of safety.⁽³⁵⁾

Plant Safety

Airborne uranium particles are a health hazard to plant personnel, particularly in the form of heavy-metal poisoning. Consequently, all machining locations must be provided with filtered exhaust lines to carry off any uranium fines. Velocities of 150 to 200 feet per minute in conjunction with a line carrying velocity of approximately 3500 feet per minute, are generally acceptable for lathes, milling machines, and grinders. While flexible suction hoses are satisfactory for most machining operations, grinding operations require a hood. All ventilation systems need filters, and they must be cleaned frequently.⁽³⁶⁾

Uranium particles smaller than 270 mesh also constitute a fire hazard. Such particles ignite spontaneously at only 68 F and burn at a temperature exceeding 1800 F. The uranium burns brightly giving off a large quantity of radiant energy. When the brightness subsides, the ashes continue to emit a red glow. Such fires can obviously cause considerable damage to equipment and the work-piece. Consequently, chips and swarf should be kept submerged in cutting fluid during machining operations to minimize the possibility of fires, and the spread of minute particulate matter in the air. Other precautions that will prevent or minimize uranium fires are as follows.⁽³⁶⁾

- Large accumulations of uranium swarf (thin chips or fine particles) on or around machine tools should not be permitted.
- Light feeds and shallow depths of cut should be avoided since they produce highly combustible swarf.
- The cutting zone should be flooded with a noncombustible fluid. A large cutting fluid reservoir should be maintained under the work area to catch and quench the hot chips.
- Fine uranium particles should be flushed frequently from the machine surfaces and the ventilation ducts.

Chip Handling

The machinist must keep the chips submerged in coolant during machining operations. When chip accumulation in the pan is no longer adequately covered with fluid, the machinist must remove the accumulation to a covered container, preferably a 55-gallon drum stationed nearby. This drum need not contain water or coolant, but at no time should there be more than one drum of chips at a machine. The drum cover should have an apron to prevent any sparks from dropping into the drum and igniting the wet chips. The lids should remain closed when the drums are in transit to provide ample protection at all locations.⁽³⁵⁾

There is no fixed length of time that chips may remain in a drum at a machine. The time can vary from an hour to a week, depending on the machining load. However, uranium chips must not be stored in a closed container for longer periods of time because hydrogen can be produced by the action of uranium with water, which provides the conditions for a possible explosion. Drums, when full of chips, are moved to an outside dock where they are emptied into a water-filled truck-transportable container. Chips thus collected are then buried or sent to another building where they are processed into briquettes for reuse.⁽³⁵⁾

Fires are practically nonexistent when the chips are kept submerged in coolant and the containers are kept covered. Occasionally, however, when procedures are not followed, fires will occur at a machine or in a storage drum. A fire at a machine is extinguished best by submerging the burning mass in coolant; fire in a storage drum is smothered or controlled by applying carbon dust. Plastic bags of powdered graphite (10 to 30-pound sizes) can be kept in metal drums near machining areas. These bags are removed from the drum and tossed on top of a chip fire. Bagged graphite does the job without the accompanying waste and scattering that occurs when loose powder is shoveled from a drum to a fire. Other extinguishing agents, such as Mat-L-X powder and dry sand, have also been found to be satisfactory.⁽³⁵⁾

Due to the extreme heat that is created during a chip fire in a drum, water must not be used inside a building to control a drum fire. Once the fire is controlled with carbon dust, the drum should be removed to an outside area and then flooded with water. It must be kept in mind that the finer the turnings, the more care is required to prevent ignition.

Adequate respiratory protection must be used in the vicinity of metal fires.

Carbon dioxide foam must not be used because hot uranium will react with the gas.

MACHINING OPERATIONS

General Information

Problems inherent in machining uranium can be minimized considerably by providing the proper cutting environment.^(35,36,37,38) This means rugged machine tools, rigid setups, high-quality cutters and appropriate speeds, feeds, and cutting fluids.

Machine Tools. Machine tools used when machining uranium should have a number of basic characteristics to insure rigid, vibration-free operations. They include:

- (1) Dynamic balance of rotating elements
- (2) True running spindle
- (3) Snug bearings
- (4) Rigid frames
- (5) Ample power to maintain cutting speed
- (6) Easy accessibility for maintenance.

Milling machines and lathes also should have backlash-elimination devices, and snug, clean, correctly lubricated gibs and slides.

Rigidity. Rigidity is a prime requirement for highly work-hardenable metals like uranium. It is achieved by using stiff tool-toolholder systems, and adequate clamps or fixtures to minimize deflection of the workpiece and tool during machining.

In milling operations, large-diameter arbors with double arm supports; short, strong tools; rigid holding fixtures; and frequent clamping are desirable.

Rigidity in turning is achieved by machining close to the spindle, gripping the work firmly in the collet, using a short tool overhang, and providing steady or follow rests for slender parts.

Drilling, tapping, and reaming require short tools, positive clamping, and backup plates on through holes.

Cutting Tools. High-quality cutting tools are needed for all machining operations. They should be properly ground and finished. The face of the tool should be smooth and the cutting edges sharp and free of burrs. Sharp tools help to assure a positive cut and to lessen the work-hardening response.

Milling cutters, drills, and taps should be mounted to run true. Lathe tools usually should cut on dead center. In a multiple-tooth cutter, such as mill or drill, all teeth should cut the same amount of metal.

The high strain hardening rate and high tool tip temperatures associated with uranium machining require that most cutting tools for uranium be tipped with carbide. Cratering caused by these two phenomena is the primary reason for tool failure when machining uranium. Special grades of carbide have been developed through the efforts of the carbide manufacturers and machining personnel in the uranium industry. This development has yielded tools composed predominantly of tungsten carbide (WC), with a high percentage of tantalum carbide to provide a high degree of crater resistance. The following tabulations list some of these tool materials and their compositions.^(36,37)

Carbide Manufacturer	Composition, percent			Potential Use
	TaC	WC	Co	
Kennametal 6972 Firth Sterling WL	20	72	8	For brazing to steel (drilling, reaming, boring, form tooling)
Kennametal 5860 Carboloy X4520	40	52	8	For inserts (turning)
Carboloy 44A	—	94	6	

Cutting Fluids. Cutting fluids are required during machining operations on uranium and uranium alloys. The flow must be forceful and continuous because erratic or interrupted flow on a working cutting edge will do more harm than good, particularly on carbides.

Cutting fluids perform six functions during the machining of uranium - specifically⁽³⁶⁾:

- Prevent fires by quenching the swarf as it is generated
- Reduce airborne contamination
- Reduce the tool-work coefficient of friction in some machining operations
- Inhibit corrosion of metal surfaces
- Carry away uranium swarf
- Remove heat from cutting zone.

Soluble oils such as Dasco 900, Texaco C, Sun Oil "SECO", or Irmco-330, diluted 30:1 with water can be used freely in large quantities during metal removal operations. A synthetic type of cutting fluid, Rustlick "BX", also can be used. Diluted with 50 parts of water, this type is suited for hacksawing, circular sawing, and abrasive cut-off operations. It has superior quenching ability due to a higher percentage of water.⁽³⁵⁾

The Machining Data Handbook⁽³⁹⁾ has an excellent section on cutting fluid selection and use. It lists both light and heavy duty grades of emulsifiable oils (Types 4 and 5) and synthetics (Types 6 and 7) as being suitable for the machining of uranium. Type numbers are cross referenced with commercially available cutting fluids.

Since uranium is highly susceptible to pitting in aqueous solutions, certain controls have been established as follows: (1) water-soluble oil ratio should be 30:1 or higher, and (2) concentration of the chloride ion should be maintained at less than 50 ppm. The pitting rate increases markedly if these limits are not closely observed. However, higher concentrations of the chloride ion can be tolerated when proper additions of sodium nitrite are used.⁽³⁶⁾ Generally speaking, fluids containing chlorides should be avoided because of grain boundary attack. Chlorinated organic cutting fluids must also be avoided since ship fires in the presence of such materials can cause phosgene gas.⁽³⁵⁾

The pan of each machine used in machining uranium should always contain enough fluid to cover a reasonable accumulation of chips. Without this precaution, the machined chips may ignite and continue to burn, producing an extremely hot fire and a health hazard to personnel.⁽³⁵⁾

Each machine may operate on its own cutting fluid supply, or a central cutting fluid system can be used to supply several machines. Such a system reduces temperature buildup in the cutting fluid,

and allows the uranium fines to settle out. This settling system, together with filters at strategic points, insures the capture of practically all the metal particles.⁽³⁷⁾

Machine sumps must be cleaned periodically to remove uranium oxide and finely divided metal. In doing so, care must be taken in handling and disposing of this material from both the safety and environmental pollution standpoints.⁽³⁵⁾ This procedure was described earlier.

Surface Finish. Surface finishes obtained when turning uranium have values of 64 to 250 micro-inches for roughing, 32 microinches for finishing, and 15 microinches for fine finishing. Milling operations achieve essentially the same quality of finishes as turning. The conditions used for grinding result in surface finishes in the range of 20 to 30 microinches. By varying conditions, finer finishes may be obtained, but the resulting dust must be handled with extreme caution since it is very pyrophoric. This form of uranium has been known to ignite under water.⁽³⁵⁾

Milling Operations

Very little difficulty should be experienced in milling uranium alloys.^(35,36,37) Carbide milling cutters, good cutting fluids, and moderate feeds and speeds are essential for good results.

Machine Tools. The design and construction of modern machine tools usually provide the rigidity and power needed for milling uranium. The improved spindle bearings allow greater cutting loads and speeds, the fly wheel insures constant cutter speed throughout cutting, and dynamically balanced rotating elements eliminate vibration. These machines can take full advantage of the latest advances in tooling and machining methods, and the resulting production is significantly higher than with older machines.

Cutters. Face mill diameters are important. They should be as wide as possible but not appreciably wider than the width of the cut. It is not good practice to bury the cutter in the work.

Fixturing. Fixtures should hold and support the workpiece as close to the machine table as possible. The solid part of the fixture (rather than the clamps) should absorb the cutting forces. The fixtures themselves should be rugged enough to minimize distortion and vibration.

Operations. The selection of speeds, feeds, and depths of cut should take into account the rigidity of the setup, optimum metal removal, tool life values, and the surface finish and tolerances needed on the finished part. Cutters, fixtures, and the milling machine must not be overloaded.

Water-based soluble oils and chemical coolants are used extensively, and are flood applied to quench any sparking and to cool the workpiece.

Tables 20 and 21 contain data on feeds, speeds, depths of cut, and tool designs which have been successfully used by those experienced in the machining of uranium.

TABLE 20. MACHINING CONDITIONS FOR MILLING URANIUM AND ITS ALLOYS

Machining Parameters	Machining Operations	
	Rough	Finish
Speed, fpm	150 ^(a)	200 to 250 ^(b)
Table Feed, ipm	2.5 to 3 ^(a)	1.5 to 2 ^(b)
Depth of Cut, inch	0.050	0.005 maximum
Tool Geometry:		
Rake Angle, degrees	+5 (maximum)	+5 (maximum)
Clearance Angle, degrees	7	10
Nose Radius, inch	0.03 to 0.05	0.020 to 0.040
Carbide Grade	C-2 ^(c)	74WC-20TaC-6Co
Coolant ^(d)	Soluble oil/water	Soluble oil/water

(a) Adjust conditions to obtain a 0.002-inch feed per tooth (approximately).

(b) Adjust conditions to obtain a 0.001-inch feed per tooth (approximately).

(c) CISC grade by Carbide Industry Standardization Committee.

(d) Five percent soluble oil, 95 percent water.

TABLE 21. MACHINING CONDITIONS FOR HOLLOW MILLING URANIUM ALLOYS

Machining Parameters	Machining Operations	
	Rough	Finish
Speed, fpm	350	425
Feed, ipt	0.020	0.020
Depth of Cut, inch	0.030 to 0.040	0.020 to 0.030
Cutting Tool:		
Type Insert	3/4 inch circular	3/4 inch circular
Rake Angle, degrees	-5	-5
Tool End Point, inch (wearland)	0.020	0.015
Carbide Grade	52WC-40TaC-8Co	52WC-40TaC-8Co
Coolant	Soluble oil (30:1)	Soluble oil (30:1)

Drilling Operations

Drilling can be a difficult operation to perform on depleted uranium alloys if good machining practices are not used.^(35,36,37) Work hardening can be minimized by using sharp drills with thin webs, together with constant positive feeds.

Difficulties resulting from poor drilling action may include out-of-round, tapered, or smeared holes. These can cause problems in any subsequent rearming or tapping operation. These difficulties can be minimized by designing holes as shallow as possible, using short, sharp drills with large flutes and special points, flushing the tool-chip contact site with a suitable cutting fluid, and employing suitable speeds and positive feeds.

Machine Tools. Drilling machines must be sturdy and rigid enough to withstand the thrust and torque forces built up during cutting. Hence, the spindle overhangs should be not greater than necessary for a given operation. Excessive clearances in spindle bearings cannot be tolerated, and the radial and thrust bearings should be sufficient to minimize runout and end play.

Drills. Drill strength and rigidity are highly important factors in successfully drilling uranium alloys. Generally speaking, drills are made from M1 high-speed steel with carbide inserts, they incorporate helical designs, polished flutes, and short lengths. The length of the drill should be kept as short as possible, not much longer than the intended hole, to increase columnar rigidity and to decrease torsional vibration that causes chatter and chipping.

High-volume production drilling requires the use of carbide-tipped oil-hole twist drills. Oil-feeding drills cool, lubricate, minimize welding, and help in chip removal. Solid carbide drills with Suiflo paste lubricant seem to be better than carbide-tipped drills when drilling small holes.

Fixturing. Drill jigs and bushings are used whenever added rigidity is needed for the setup. When drilling stacked sheets, the sheets should be clamped securely with clamping plates to eliminate gaps between sheets.

Operations. Setup conditions selected for drilling should provide overall setup rigidity, and sufficient spindle power to maintain drill speed during cutting. Successful drilling of uranium also depends on minimizing cutting temperature. This is accomplished by using moderate cutting speeds, positive feeds, and adequate cooling at the cutting site. The drill should never ride in the hole without cutting since the rubbing action promotes work hardening and rapid dulling of the cutting edge. Generally, a feed range of 0.001 to 0.004 inch per revolution is used, the actual rate being a function of the drill diameter.

Drilling uranium requires a steady full flow of soluble oil (30:1), externally applied. However, a limiting hole depth of twice the diameter seems to exist for external applications of cutting fluids. Hence oil-feeding or oil-hole drills work best for deep holes. Soluble oil (30:1) at a pressure of 250 psi or more has been used to force chips out of the flutes.

When starting the drilling operation, the drill should be up to the required speed and under positive feed as it contacts the work. The drill should be pulled out of the hole frequently (to free

it from chips and to permit periodic cooling of the drill) unless the cutting fluid successfully flushes away the chips.

Table 22 presents some typical setup data for drilling uranium.

Precautions. The margin of the drill should be examined periodically for smearing as well as for breakdowns that might occur at the outer corner of the lips. A safe drill replacement life should be established to prevent work and drill spoilage.

Tapping

Tapping is a more difficult operation than drilling because of the abrasiveness of uranium against the cutting edges of the tap as the chip is formed.^(35,36,37) The problems involve a sluggish chip flow and severe work hardening. As taps dull and cutting temperatures rise, consequent welding on the cutting edges and flanks of the taps produce oversized holes and rough threads. Galling also increases friction and torque requirements, and the additional torsional strain distorts the lead of the tap. Tapping stresses increase until the tap seizes and breaks.

Tapping Machines. A lead-screw tapping machine is recommended to insure proper lead, a regulated torque, and uniform hole size. However, machine tapping, unless done on a sensitive machine by a competent operator, can result in excessive tap breakage and poor quality work.

Taps. Spiral pointed taps are used when tapping uranium. Their inherent shearing action produces the least resistance to thrust. Furthermore, the entering angle deflects the chips so that they curl ahead of the tap. This minimizes packing in the flutes, a frequent cause of tap breakage.

The number of flutes in a tap is also important. A four-flute design on small taps is more liable to promote congestion than the two fluted tap that allows more chip room. The smaller number of flutes also assures more strength in the shank of small taps.

High-speed steel taps (M10, M7, M1) are usually used for tapping uranium alloys. Nitriding also proves beneficial by increasing the wear resistance of the cutting edges. Carbide taps are usually impractical.

Operations. The tap should be mounted in a properly aligned holder to avoid breakage during tapping. In addition, the shortest tap possible for the hole being tapped should be used for maximum tool rigidity. Lead-screw tapping is recommended since it is less dependent on the operator.

Tapping speeds should be limited to values between 12 and 15 feet-per-minute surface speed, although some investigators have used as high as 50 surface feet per minute.

The selection of tapping lubricants is important because of the susceptibility of taps to seizure. Molybdenum disulfide base tapping compounds, or white lead and tapping compound (3:1) have been used. Soluble oils are unsatisfactory for tapping because they lack the extreme-pressure properties needed to withstand the cutting pressures involved.

TABLE 22. SETUP CONDITIONS FOR DRILLING URANIUM ALLOYS

Drilling Parameter	Drilling Operation	
	Conventional	Automatic
Speed, fpm	20 to 25	302
Feed, ipm	0.001 to 0.015	0.001 to 0.004
Drill Design:		
Drill Type	Standard	Oil-Hole
Helix angle, degrees	—	14
Point angle, degrees	118	118
Web thickness, inch	—	0.068 or 0.098 ^(a)
Radial rake, degrees	—	(b)
Lip land, degrees	—	-5
Drill Material:		
Shank	M1 or M10 high-speed steel	M1 or M10 high-speed steel
Tip	Carbide C-2	Brazed Carbide (72WC-20TaC-80Co)
Cutting Fluid	Soluble oil/water (10:90)	Soluble oil/water (1:30) at 250 psi pressure)

(a) Depends on thickness of carbide insert.

(b) Neutral rake angle for drills less than 1/2-inch diameter; -5 degrees for drills 1/2-inch diameter and greater.

Tapping difficulties can be minimized by reducing the thread requirements to ranges suitable for specific applications. Thread depths should be somewhere in an overall range of 50 to 75 percent. Sixty-five percent is a value sometimes used by those experienced in machining uranium. Suitable thread lengths in uranium involve tapping the fewest threads the design will allow.

Designs should also avoid specifying blind holes in uranium alloys. Also, some relaxation in class-of-fit tolerances should be considered when uranium alloys are tapped.

Clean, round holes are essential for tapping. Hence, such holes should have been produced by sharp drills operating under proper drilling conditions. Dull drills produce surface-hardened holes that magnify tapping difficulties.

Immediately before tapping a hole, the tap should be covered with a liberal amount of white lead and tapping compound. Taps should be inspected carefully after each use for possible smearing of tap lands. The workpiece also should be inspected for possible torn threads and dimensional discrepancies. It should be remembered that most tapping is done on parts that are 80 to 90 percent finished.

Turning and Boring

Turning and boring operations are the easiest machining operations to perform on uranium alloys. These operations, nevertheless, must cope with the high work hardening rate of these alloys, and this means heavy duty machine tools, rigid setups, proper tool materials, and appropriate cutting conditions ^(35,36,37)

Machine Tools. Lathes with 10-horsepower ratings should be suitable for most turning operations. Workpieces ranging between 1 and 10 inches in diameter can be turned on a heavy-duty 1610 engine lathe. These lathes have the required range of spindle speeds, and will meet the machine-tool requirements described earlier.

Cutting Tools. Standard cutting tools are used for turning uranium alloys, and are available in a variety of shapes, sizes, tool angles, and tool materials. Carbide cutters are normally used. They are available as brazed tools or as multi-edge, indexable inserts designed to be held mechanically in either positive- or negative-rake tool holders of various styles and shank sizes.

Operations. The work should be firmly chucked in the collet of the spindle and supported by the tail stock using a live center. Machining should be done as close as possible to the spindle for minimum work overhang. A steady or follow rest should be used to add rigidity to slender parts. The cutting tool should be held firmly in a flat-base holder with minimum overhang to avoid tool deflection. It should cut on dead center.

Table 23 shows some typical turning data for uranium alloys. Cutting speeds between 150 and 450 fpm can be used when turning uranium alloys, depending on the feed, depth of cut, tool material, and cutting fluid being used for the operation (rough, finish, etc.).

TABLE 23. TURNING, BORING, AND FACING URANIUM ALLOYS^(a)

Maching Parameter	Machining Operations ^(b)		
	Rough	Finish	Fine Finish
Speed, fpm	150 - 200	275 - 325	425 - 450
Feed, ipm	0.012-0.018	0.002-0.003	0.001-0.002
Depth of cut, inch	0.05-0.010	0.002-0.005	0.0001-0.0005
Cutting Tool:			
Rake angle, degrees	-5 or 0	+5 or 0	0
Clearance angle, degrees	5	7	7
Nose Radius	0.047	0.020-0.025	0.020-0.025
Carbide Cutter	72WC-3TiC- 11TaC-9Co	74WC-20TaC- 6Co	37WC-57TaC- 6Co

(a) Boring and facing same conditions as for turning except that cutting speed should be decreased by 10 percent.

(b) Using a 2 percent inhibitor and water coolant.

Turning operations for these materials require constant, positive feeds throughout machining. Dwelling, stopping, or deliberate slowing up in the cut must be avoided. Feeds should be as heavy as the surface-finish requirements and the strength of the alloy will allow.

The depth of cut will depend on the amount of metal to be removed, the metal-removal rate desired, and the turning operation undertaken. The tool should get under any oxide in clean-up operations.

For second cuts, the nose of the tool should get below any work hardened surface remaining from previous processing operations. This second cut may notch the tool at the depth-of-cut line. In finish turning, light cuts are normally used for the best finish; however, a fire hazard may exist due to the fine chips produced.

Water-base coolants are always used to cool the tool, to reduce the fire hazard of uranium chips, and to aid in chip removal. A full, steady flow should be maintained at the cutting site for maximum effect, particularly for carbide tools.

During machining, the chips should be expelled from the cutting site as promptly as possible, particularly during boring operations. Chips lying on the surface tend to produce chatter and poor surface finishes.

The tool should be examined frequently for nicks and worn flanks. These defects promote galling, increase cutting temperature, accelerate tool wear, and increase residual stresses in the machined surface. Arbitrary tool-changing schedules are often used to insure sharp tools. This usually means replacing carbide tools after a 0.015-inch wearland in rough turning, and after a 0.010-inch wearland in finish turning.

GRINDING OPERATIONS

Uranium and its alloys can be ground at about the same rate as hardened high-speed steels and die steels.^(35,36,37) Moderately light cuts are recommended, and periodic dressings are required to keep the wheel in proper condition. Excessive wheel loading leads to poor grinding action and causes poor surface finish, high residual tensile stresses, and low grinding ratios. As loading continues, the grinding action decreases until burnishing occurs. Then the grinding temperature rises and causes high residual tensile stresses in the ground surface and generally an unsatisfactory surface finish.

Grinding difficulties can be minimized by employing the proper type wheels at appropriate wheel speeds and feeds, and by flooding the grinding area with inhibitor or soluble oil types of cutting fluids.

Equipment and Setup. Uranium and uranium alloys have similar grinding characteristics except that the former may allow a little better wheel life. In both cases, there is a very limited operating range, hence, care must be taken to establish rather precise grinding conditions.

The following recommendations are suggested in order to provide the good grinding conditions needed for uranium.

- High quality grinders with variable speed spindles
- Rigid set up of work and wheel
- Rigid mechanical holding fixtures
- Arbors for external grinding
- Oxidized machine centers to prevent galling of small parts
- Backing whenever necessary to overcome deflection of the work.

Grinding Wheels. Silicon carbide wheels seem to be preferred for producing the best surface finish. However, recent production experience with U-3/4Ti⁽³⁾ indicated that the recommended silicon carbide wheels for uranium and wheel grades bracketing these recommendations were inferior to aluminum oxide. The wheel grades should be chosen using the following as guides:

- The largest practical diameter and width of wheel should be used
- Grits should possess the characteristics of progressive fracture as the primary wear mode
- The abrasive grain should be of optimum size; smaller sizes allow whole grains to leave the wheel prematurely, and higher wheel wear results
- The hardest wheel that will not cause burning or smearing should be used
- Vitrified materials are best in that they are more porous, permit better swarf clearance, and result in grinding at lower temperatures.

Grinding Fluids. The selection of a grinding fluid is very important since the application involves not only cooling but also inhibiting the surface action between uranium and the abrasive wheel. Uranium and its alloys should never be ground dry. Dry grinding results in excessive residual stresses in the ground part in addition to the fire hazard that is present from dry uranium swarf.

Water alone is not suitable, and ordinary soluble oils do not always produce good grinding ratios although they do reduce the fire hazard of grinding.

Fluids should be filtered to remove grit and prevent "fish tail" marks on finished surfaces. Fluids should be changed more often than is customary when grinding steel.

Operations. In contrast to other metal-cutting methods for uranium, light feeds are required for all abrasive-wheel operations to produce parts with low residual stresses. Downfeeds of 0.002 to 0.005 in-per pass are not unusual.

Wheel speeds of 3000 to 5000 sfpm are used with silicon carbide wheels and inhibitor-type cutting fluids to produce a good combination of surface finish and dimensional tolerance with relatively low residual stresses.

Wheels used to grind uranium and its alloys must be dressed more frequently than those used to grind steels because of the tendency of uranium to load the wheel. This causes higher temperatures at the wheel-metal interface, thus tending to produce surface cracks and in some cases to burn the metal.

Data on speeds and feeds for silicon carbide grinding wheels are shown in Table 24.

TABLE 24. GRINDING OF URANIUM AND ITS ALLOYS^(a)

Grinding Parameters	Precision Grinding		Centerless Grinding	
Abrasive types	Regular silicon carbides, green		Regular silicon carbides, green	
Grit Size	Medium (46-80)		Medium (46)	
Wheel Grade	Soft (G or H)		Medium (I or J)	
Structure	Open (11-13)		Open (10)	
Bond	Vitrified (V)		Resinoid (B)	
<u>Operation</u>	<u>Roughing</u>	<u>Finishing</u>	<u>Roughing</u>	<u>Finishing</u>
Feed				
Down feed, in-per pass	0.005	0.002 Stock re- moved on diameter inch	0.005 ^(b)	0.002 ^(b)
Cross feed, inch	(a)	(a)		
Through feed of work, ipm	—	—	75-125	75-125
Speeds				
Table, ipm	(a)	(a)		
Wheel, sfpm	3000-5000	3000-5000	5500-6000	5500- 5000
Grinding Fluids	2 to 5 percent grinding fluid inhibitor and water		Soluble oil (30:1), Excessive ficod	

(a) Crossfeed, table speed, or rotating speed must be kept low enough to prevent burning of work.

(b) Stock removed on diameter, inch.

CAUTION— Uranium dust from grinding operations is extremely pyrophoric. Exercise great caution in handling or disposing of this material.

Grinding operations should be especially well supervised and controlled because of the amount of fine uranium particles generated. The recommended procedures should be followed without substitution. This also means that each operation should be inspected to insure that it is performed with due regard for the safety of the personnel involved.

APPLICATIONS FOR DEPLETED URANIUM

Depleted uranium and its alloys have found applications in various areas including aircraft and missile counterweights, radiation shielding, ammunition, weapons, gyrorotors, and ballast. High density is the important property in all these applications, but in some instances, the combination of high density and high strength or hardness is important. The pyrophoricity of uranium alloys is a plus for their potential uses in ammunition.^(1,40,41)

The applications for depleted uranium described in this section can be categorized into five main groups. The major areas of these groups account, or will account, for the major tonnages consumed.

GROUP I - BALLAST AND COUNTERWEIGHTS

Depleted uranium has found increasing use in ballast and counterweight applications since being first introduced in 1960. Tonnages have grown steadily from 25 in 1961 to 250 tons in the early 1970's, and probably reflect the increasing cost of tungsten. The following applications for aircraft and missiles constitute the major areas of this group.

AIRCRAFT CONTROL SURFACE COUNTERWEIGHTS

It is aerodynamically helpful to balance the weight of rudders, ailerons, and elevators around narrow hinge points. Since the space ahead of the hinge point is usually limited (which results in a short lever arm), it is advantageous to use a dense material like depleted uranium or tungsten.

Depleted uranium counterweights for this application are produced mostly as castings in a variety of shapes and sizes that may weigh from a few ounces to several hundred pounds per aircraft.

BALANCING AND VIBRATION DAMPING

Depleted uranium has been used for structural vibration damping, weights on leading edges of helicopter rotors, and counterweighting items other than control surfaces. The use of depleted uranium in the third application includes:

- Airborne radar antennae control
- Control instruments for guided missiles
- Motor vibration damping
- Camera-shutter timing mechanisms

The high inertial rotational applications include:

- Gyroscope rotors
- Governors
- Centrifugal clutches
- Gyro bombsights

- Torsional vibration damping
- Gyro automatic pilots.

An interesting application of depleted uranium now under development is its use in an oil well drill collar. The depleted uranium section is located at the bottom of the drilling column. It is 16 feet long, 7½ inches in diameter, and weighs 4800 pounds. This device is expected to improve cutting rate, reduce chatter, and keep the drill bit on course.⁽⁴¹⁾

The use of depleted uranium as a machine tool boring bar to control vibration and chatter is also under development.

MACHINERY BALLAST AND COUNTERWEIGHTS

Depleted uranium has been used in certain testing machines, and in some large crushing machinery. Although this area of use has been small, the capability of uranium fabricators to make very large castings is expected to expand this field.

ELECTROMECHANICAL COUNTERWEIGHTS

Uranium has been used in a number of electromechanical devices where high-density material is required for gimbal weights and similar functions. Uranium has also been used for the rim of gyro-rotors where density is important.

GROUP II - RADIATION SHIELDING

The very high density and high atomic number of uranium make depleted uranium a nearly ideal gamma-ray and X-ray shielding material. For example, it is being used in small isotope radiography devices. Most major producers of this equipment use uranium instead of lead, since the added cost is justified in making a more portable unit. In contrast, some very large shields (15 tons) have been made for the U.S. Navy atomic energy refueling systems.

Depleted uranium is also an attractive material for containers for radioactive materials. Regulations for such containers are very rigid. They require the shield to withstand a major accident without loss of shielding integrity, as well as to demonstrate impact and fire resistance. The high melting point and good mechanical properties of depleted uranium make it a material superior to lead for meeting these safety requirements.

The consumption of depleted uranium for the shielding of simple radioisotopes is estimated to be roughly 30 tons per year. The largest demand would be for shipping casks for spent fuels from atomic power reactors. The spent fuel, which is exceedingly radioactive, is usually in the form of 12- to 18-foot rods that are assembled in bundles or clusters. Each assembly contains from 400 to 900 pounds of fuel. The spent fuel assemblies, when removed from the reactors, are placed in casks for shipment to a processing center. This use has been expected to provide an additional consumption of approximately 1000 tons of uranium per reactor site. But the implementation of this use has been delayed pending new DOT requirements and problems in the construction and start-up of reactors.

Depleted uranium is expected to be used more widely in shielding applications because its cost decreases with expanding markets.

GROUP III - ORDNANCE APPLICATIONS

The U.S. Army's need for depleted uranium for structural or mechanical applications began in 1958 in connection with a special-purpose ammunition development program. Uranium alloys produced had the required strength and toughness for applications such as the XM-101 spotter -- a 20-mm spotting round used with the Davy Crockett Weapon System. Also, recent armor-piercing development programs utilizing depleted uranium for large caliber armor-piercing penetrators (105- and 120-mm shells) and other DU penetrators for the USAF 30-mm GE GAU-8 gun system indicate a tremendous potential for this material. Currently anticipated procurement for this system is approximately 9000 tons.

Depleted uranium alloys also can serve as a combined radiation, armor, and structural material for atomic-powered equipment.

GROUP IV - OTHER HIGH-DENSITY APPLICATIONS

The major areas involving high-density material usage include counterweights, centrifugal devices, and vibration damping other than those used in Group I applications. The possible applications in this group are limited only by the designer's imagination for a given mechanical device. The fabricating and property information contained in this report should be helpful to those seeking such new applications for uranium.

The use of depleted uranium in flywheel devices could consume a significant amount of metal. Depleted uranium would meet the increased strength requirements needed for the enormous centrifugal forces of such devices. The increased price of depleted uranium could be largely compensated for by the reduced size of the device which still would have equal power storage capacity. Since no wear occurs on these parts, they could be reused in new power units. Also, the scrap from outdated parts would be recoverable for reuse.

GROUP V - MISCELLANEOUS USES

Several minor uses of depleted uranium are suggested here to exemplify the versatility of uranium. These uses will not solve the problem of oversupply of depleted uranium, but the knowledge gained could lead to new demands for this material.

Since depleted uranium is recovered from the separation plants as uranium hexafluoride, the product (UF_6) could become a source of fluorine for producing hydrogen fluoride (HF). The uranium by-product could be UF_4 , UC_2F_6 , U_3O_8 , or UO_2 , depending on the reaction steps performed. These

compounds are convenient to store and to handle. They can be used as is, or readily converted to other uranium compounds.

The electrical properties of uranium oxides and uranates appear to be useful in the construction of fuel cells, incandescent lamps, thermistors, and as ultraviolet light-sensitive elements in photoelectric tubes. Uranium dioxide in semiconducting devices is another potential use.

The depleted uranium metal itself can be used as a getter for traces of active gases in high-vacuum work, as a purification agent for hydrogen and noble gases, and uranium compounds are used as catalysts.

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